The Nuclear Evolution of the Universe

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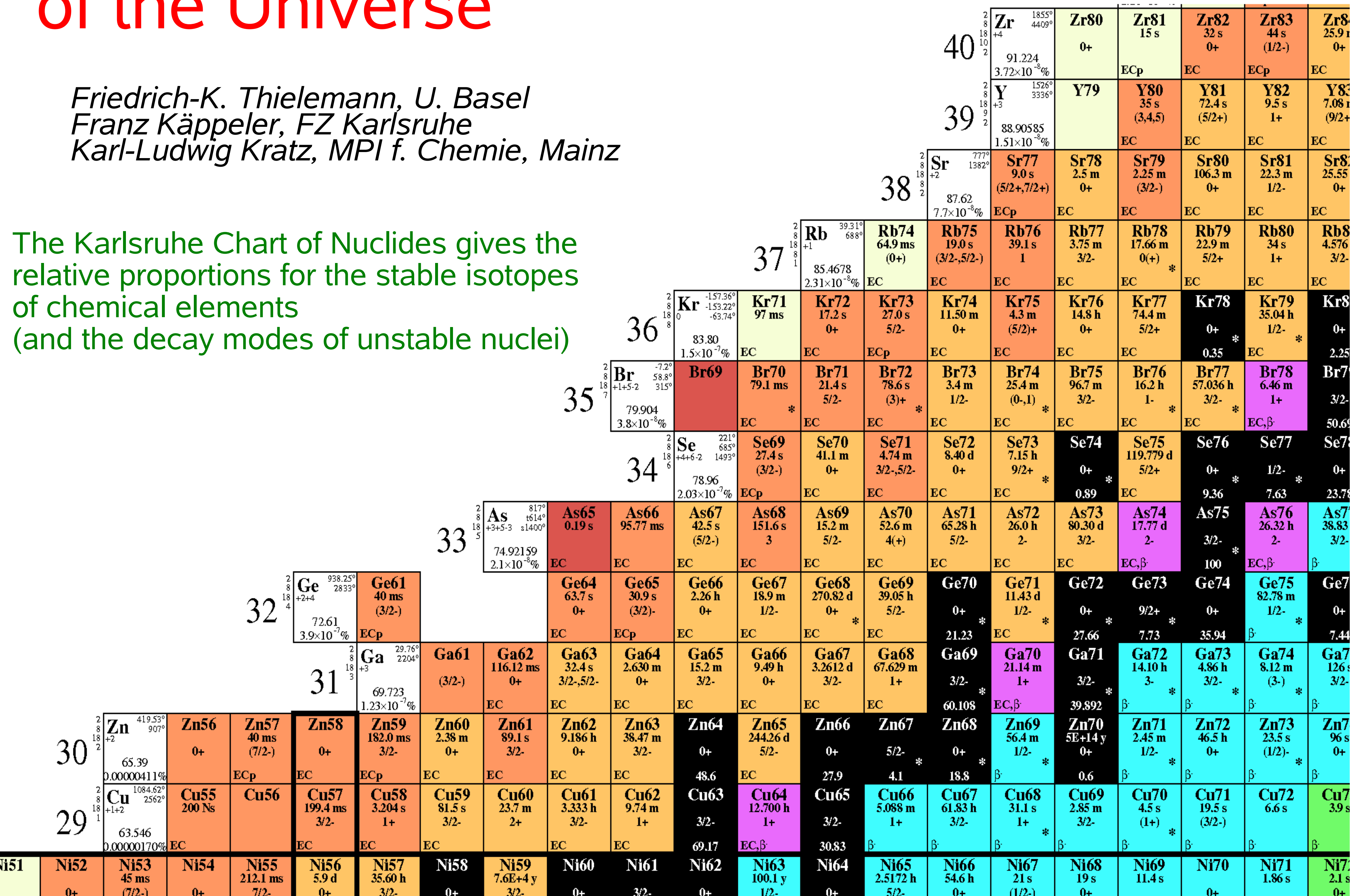
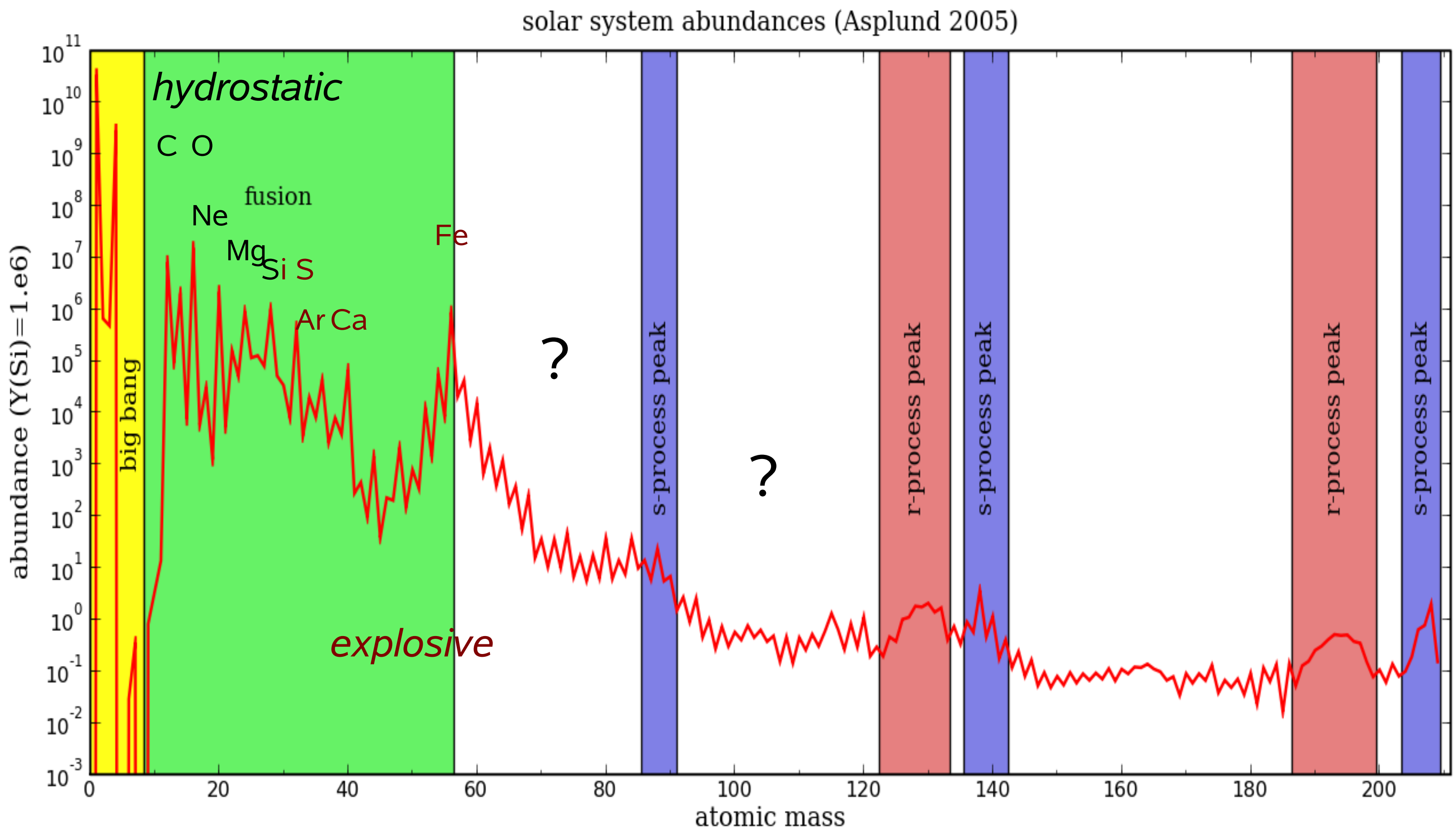
The Karlsruhe Chart of Nuclides gives the relative proportions for the stable isotopes of chemical elements
(and the decay modes of unstable nuclei)



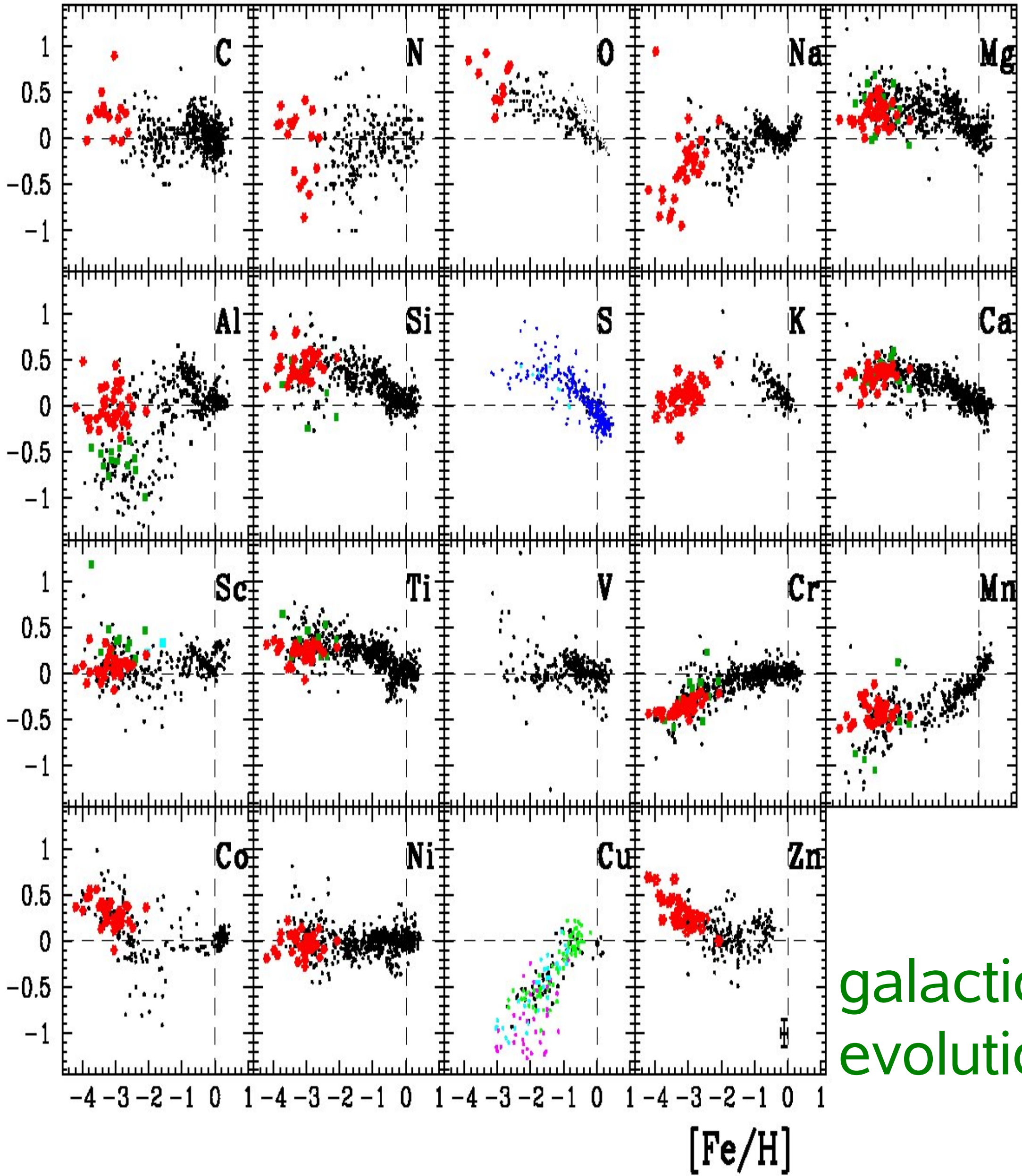
Allende Meteorite

Carbonaceous Chondrites are the most privitive meteorites, matter in their matrix seems not heated beyond 200/50C. They are formed from compacted dust in the outer parts of the solar system. Their elemental ratios reflect the global abundances in the solar system, with the exception of volatile elements (especially noble gases), which might be partially depeleted.

solar system abundance distribution (from carbonaceous chondrites and solar absorption spectra)

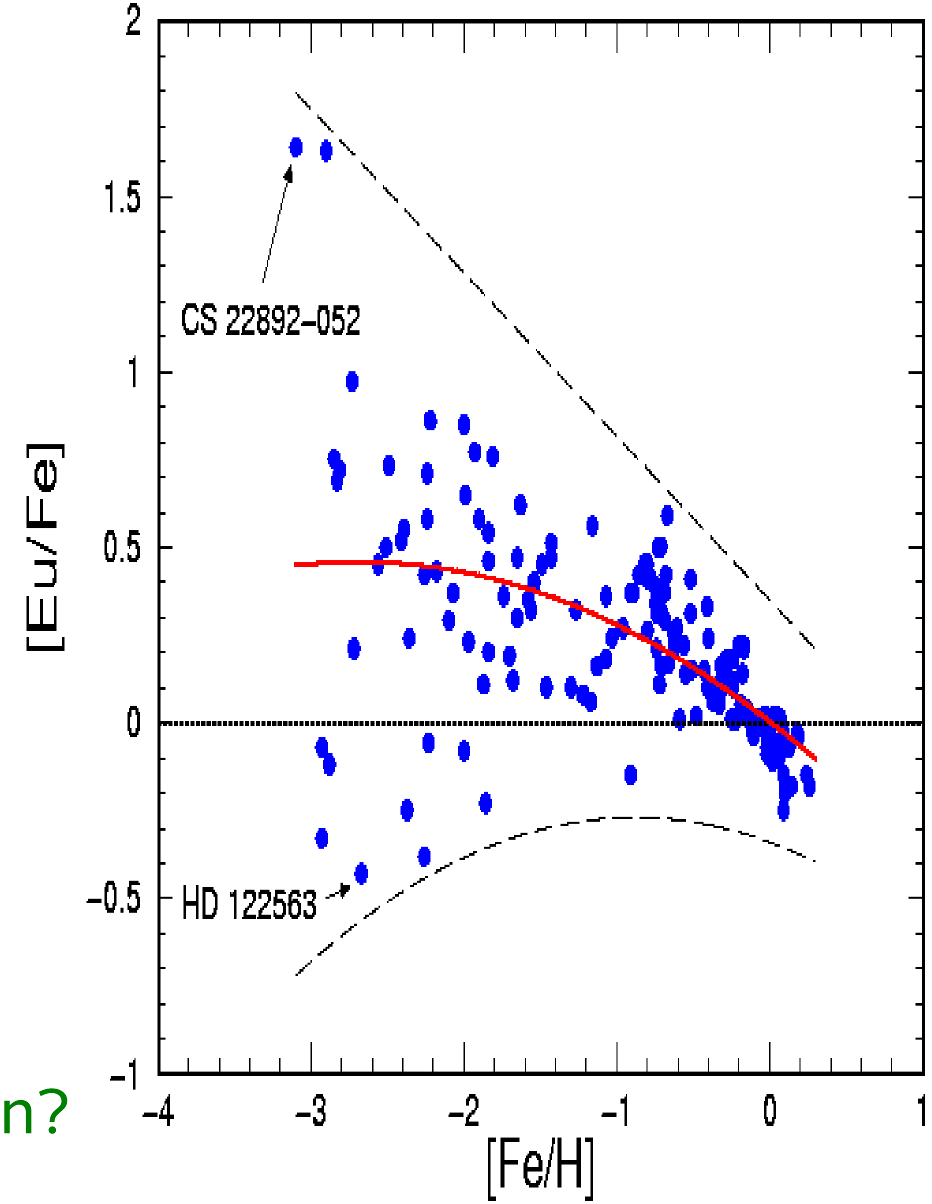


How do we understand solar system abundances.. (plotted are surface abundances of stars)

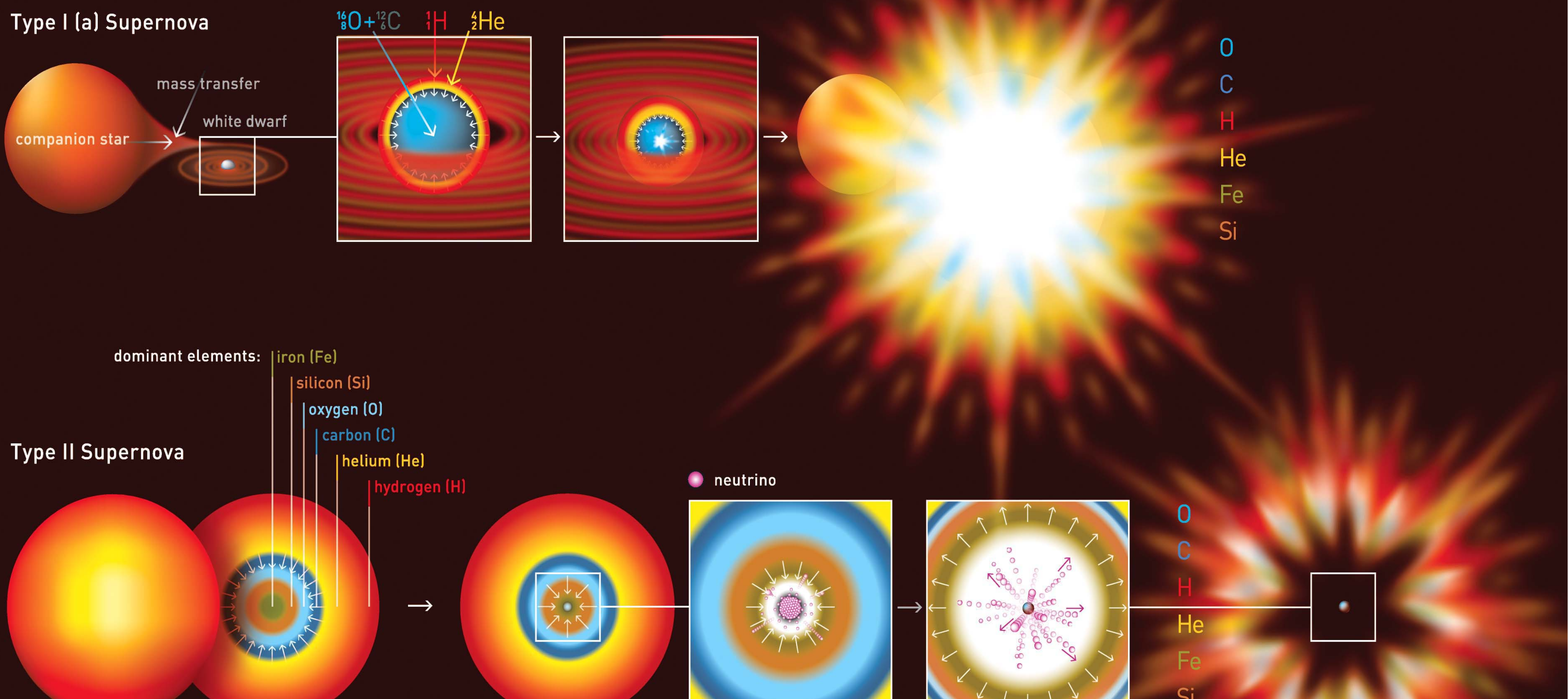


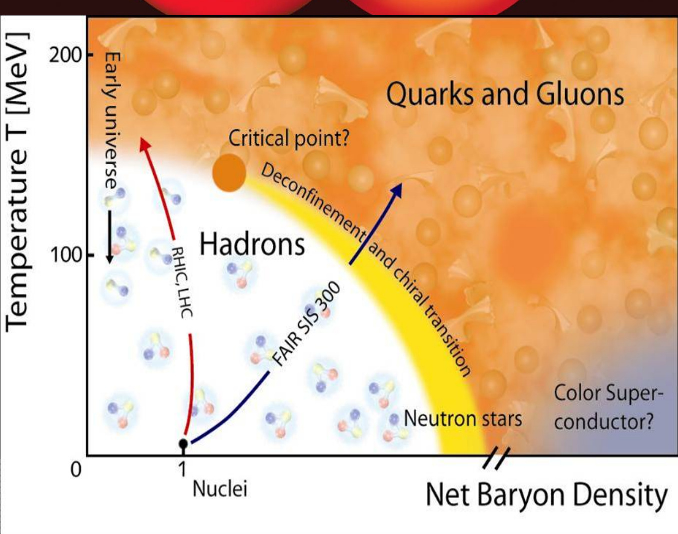
galactic evolution?

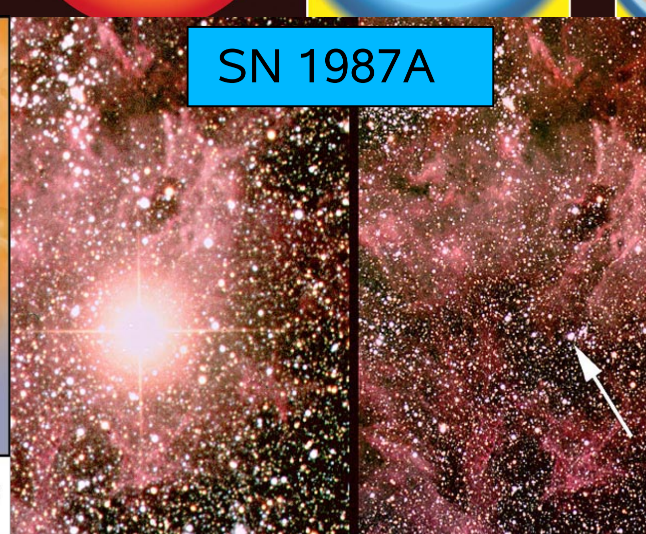
low metallicity stars ...

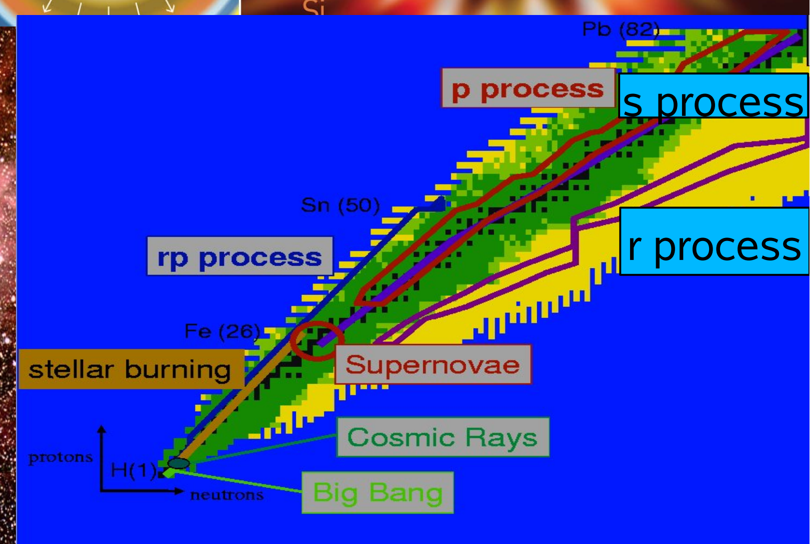


Supernovae


Type I (a) Supernova
${}^{16}_{8}O + {}^{12}_{6}C$
${}^{1}_{1}H$
${}^{4}_{2}He$
mass transfer
white dwarf
companion star
O
C
H
He
Fe
Si
dominant elements:
iron (Fe)
silicon (Si)
oxygen (O)
carbon (C)
helium (He)
hydrogen (H)
Type II Supernova
neutrino
O
C
H
He
Fe


Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Hadrons
RHIC, LHC
FAIR SIS 300
Neutron stars
Color Super-conductor?
1
Nuclei
Net Baryon Density

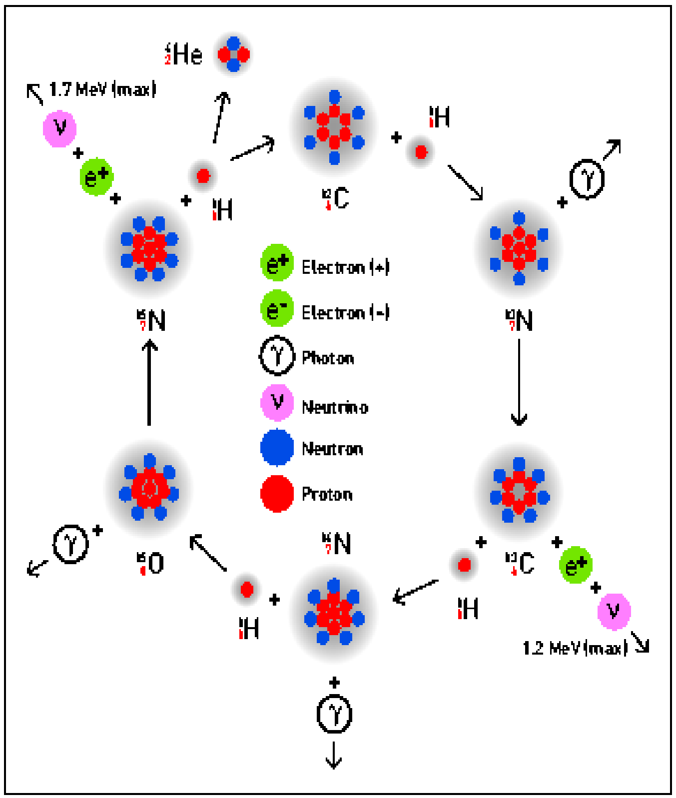

SN 1987A


Pb (82)
p process
s process
Sn (50)
rp process
r process
Fe (26)
stellar burning
Supernovae
Cosmic Rays
protons
H(1)
neutrons
Big Bang

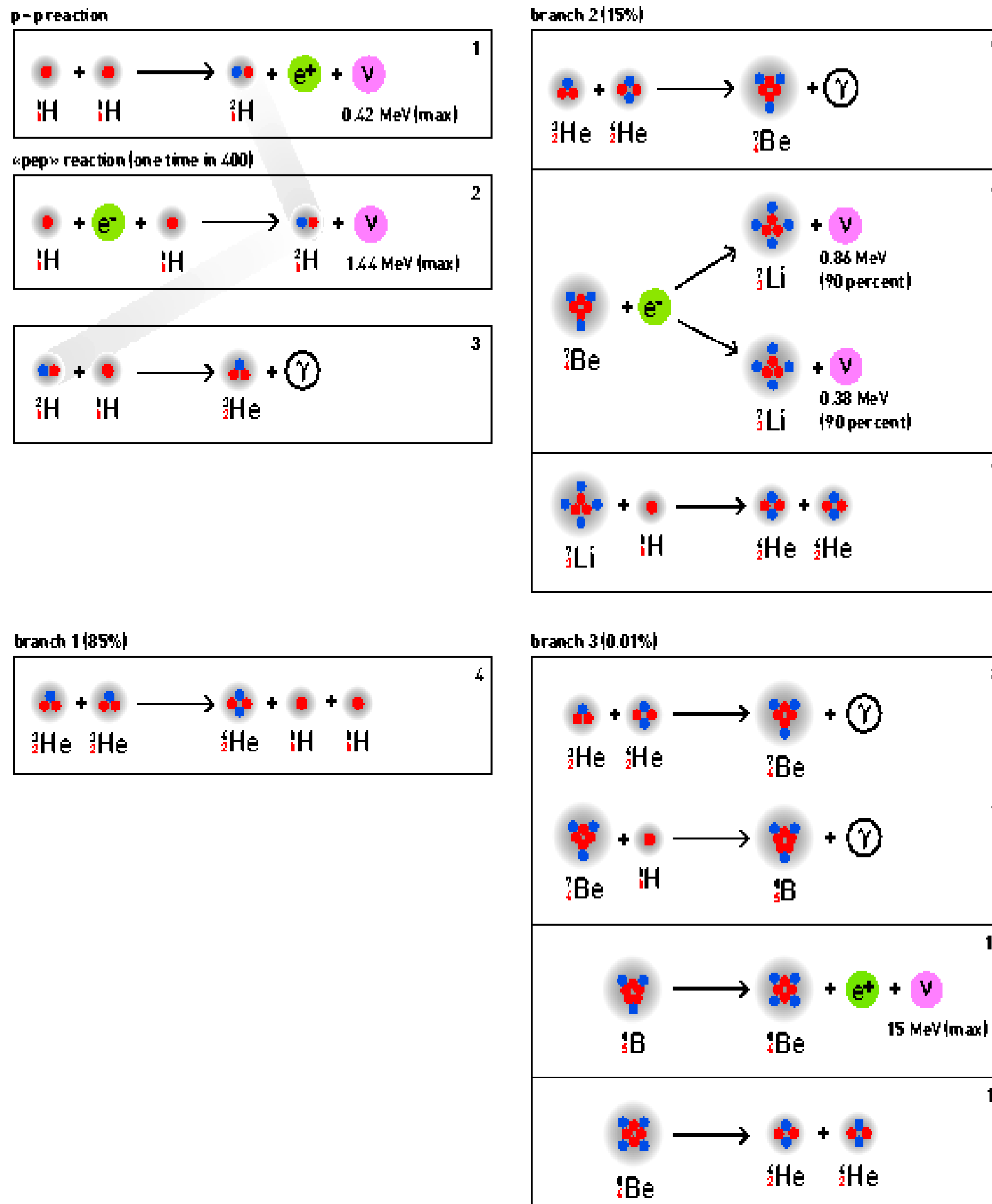
Stellar Burning Stages

Hydrogen Burning

The CNO Cycle



P-P Cycles



How do Reactions Change Compositions?

- reaction between target j and projectile k

$$\sigma = \frac{\#\text{ reactions per sec and target } j}{\text{flux of incoming projectiles } k} = \frac{r/n_j}{n_k v}$$

- for specific (velocity) distributions

$$r_{j,k} = \int \sigma |\vec{v}_j - \vec{v}_k| d^3 n_j d^3 n_k$$

- for Maxwell-Boltzmann distributions $r_{j,k} = < \sigma v >_{j,k} n_j n_k$

$$< \sigma v >_{j,k} = (\frac{8}{\mu\pi})^{1/2} (kT)^{-3/2} \int_0^\infty E\sigma(E) e^{-E/kT} dE$$

Brief Summary of Burning Stages (Major Reactions)

1. Hydrogen Burning   T = (1-4)x10^7K
   pp-cycles -> $^1H(p,e^+\nu)^2H$
   CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$
2. Helium Burning   T=(1-2)x10^8K
   $^4He+^4He \Leftrightarrow {}^8Be$ $^8Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (n-source, alternatively $^{13}C(\alpha,n)^{16}O$)
3. Carbon Burning   T=(6-8)x10^8K
   $^{12}C(^{12}C,\alpha)^{20}Ne$ $^{23}Na(p,\alpha)^{20}Ne$
   $^{12}C(^{12}C,p)^{23}Na$ $^{23}Na(p,\gamma)^{24}Mg$
4. Neon Burning   T=(1.2-1.4)x10^9K
   $^{20}Ne(\gamma,\alpha)^{16}O$
   $^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$ 30kT = 4MeV
5. Oxygen Burning   T=(1.5-2.2)x10^9K
   $^{16}O(^{16}O,\alpha)^{28}Si$ $^{31}P(p,\alpha)^{28}Si$
   ......,p)^{31}P ...,n)$^{31}S(\beta^+)^{31}$P $^{31}P(p,\gamma)^{23}S$

ongoing measurements of key fusion reactions at low energies

6. "Silicon" Burning   T=(3-4)x10^9K

(all) photodisintegrations and capture reactions possible

$\Rightarrow$ thermal (chemical) equilibrium

Global Chemical (=Nuclear Statistical) Equilibrium (NSE)

$$\bar{\mu}(Z,N) + \bar{\mu}_n = \bar{\mu}(Z,N+1)$$
$$\bar{\mu}(Z,N) + \bar{\mu}_p = \bar{\mu}(Z+1,N)$$

$$\bar{\mu}_i = kT \ln\left(\frac{\rho N_A Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right) + m_i c^2$$

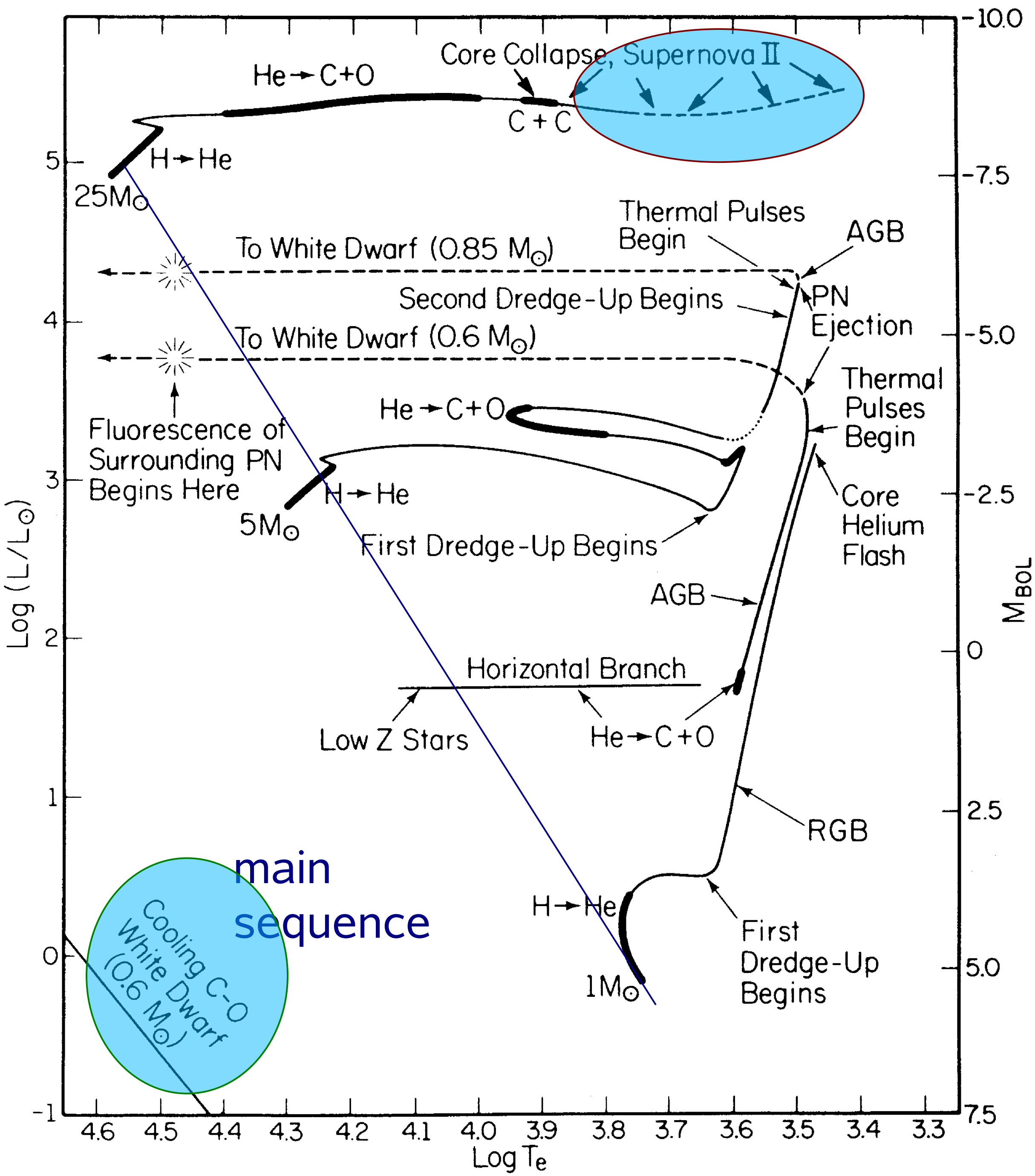
$$N \text{neutrons} + Z \;\text{ protons} \rightleftharpoons (Z,N)$$

$$N\bar{\mu}_n + Z\bar{\mu}_p = \bar{\mu}_{Z,N}.$$

$$Y(Z,N) = G_{Z,N}(\rho N_A)^{A-1}\frac{A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{\frac{3}{2}(A-1)} \exp(B_{Z,N}/kT)Y_n^N Y_p^Z$$

$$\sum_i A_i Y_i = 1$$
$$\sum_i Z_i Y_i = Y_e$$

Astrophysical Sites



Hertzsprung-Russell Diagram of Stellar Evolution from Iben, showing as end stages

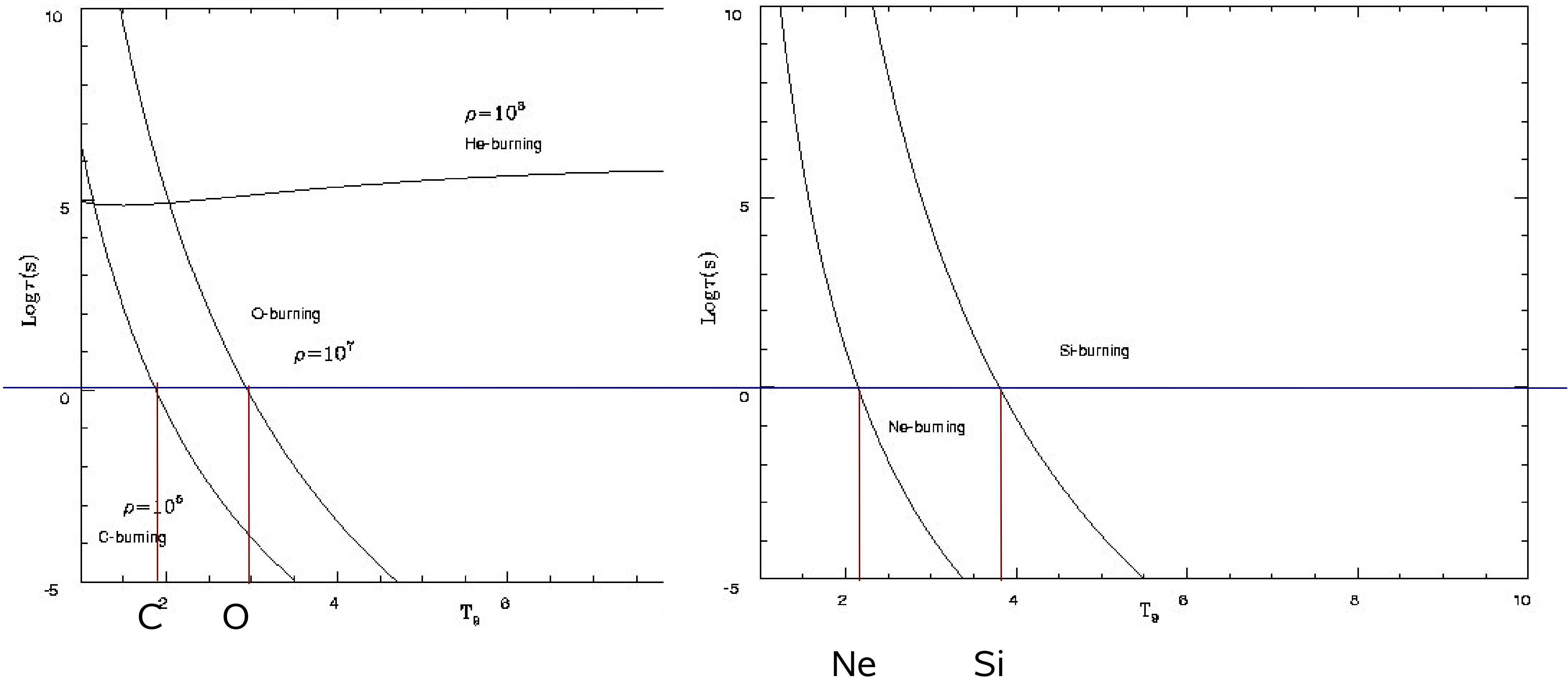
- white dwarfs

and

- core collapse (supernovae/neutron stars, black holes, GRBs?)

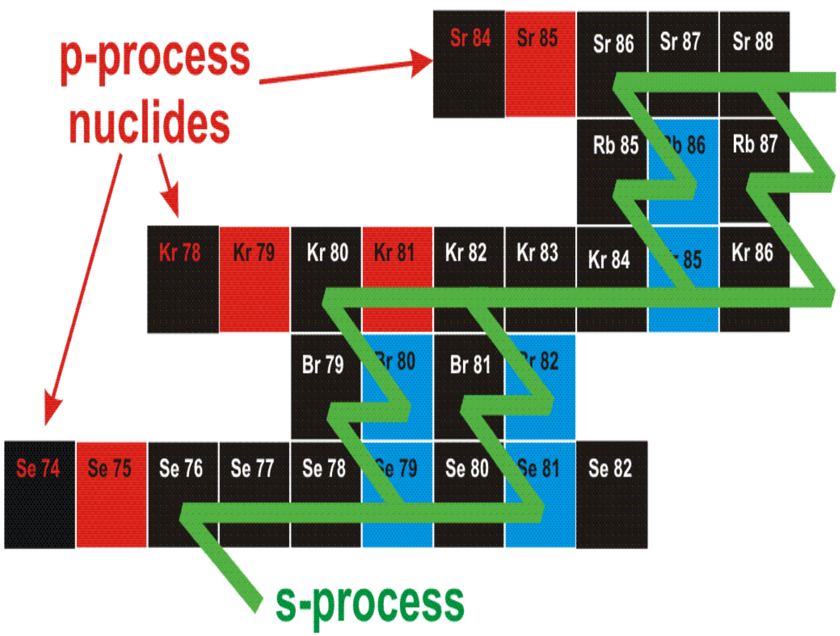
influence of reaction cross sections, e-capture in late burning stages, metallicity, rotation, magnetic fields, stellar winds on final outcome

Explosive Burning

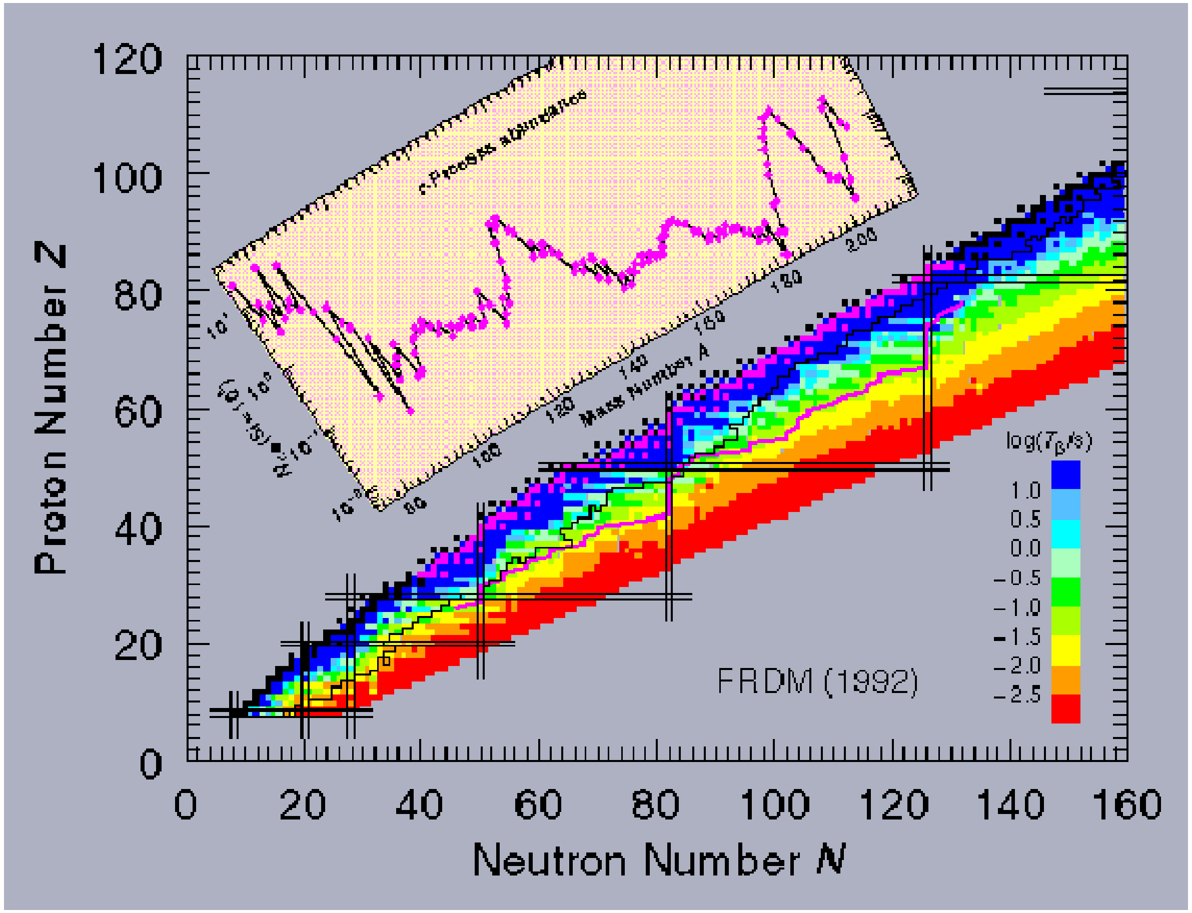


typical explosive burning process timescale order of seconds:
fusion reactions (He, C, O) density dependent (He quadratic, C,O linear)
photodisintegrations (Ne, Si) not density dependent

s-, r- and p-Process

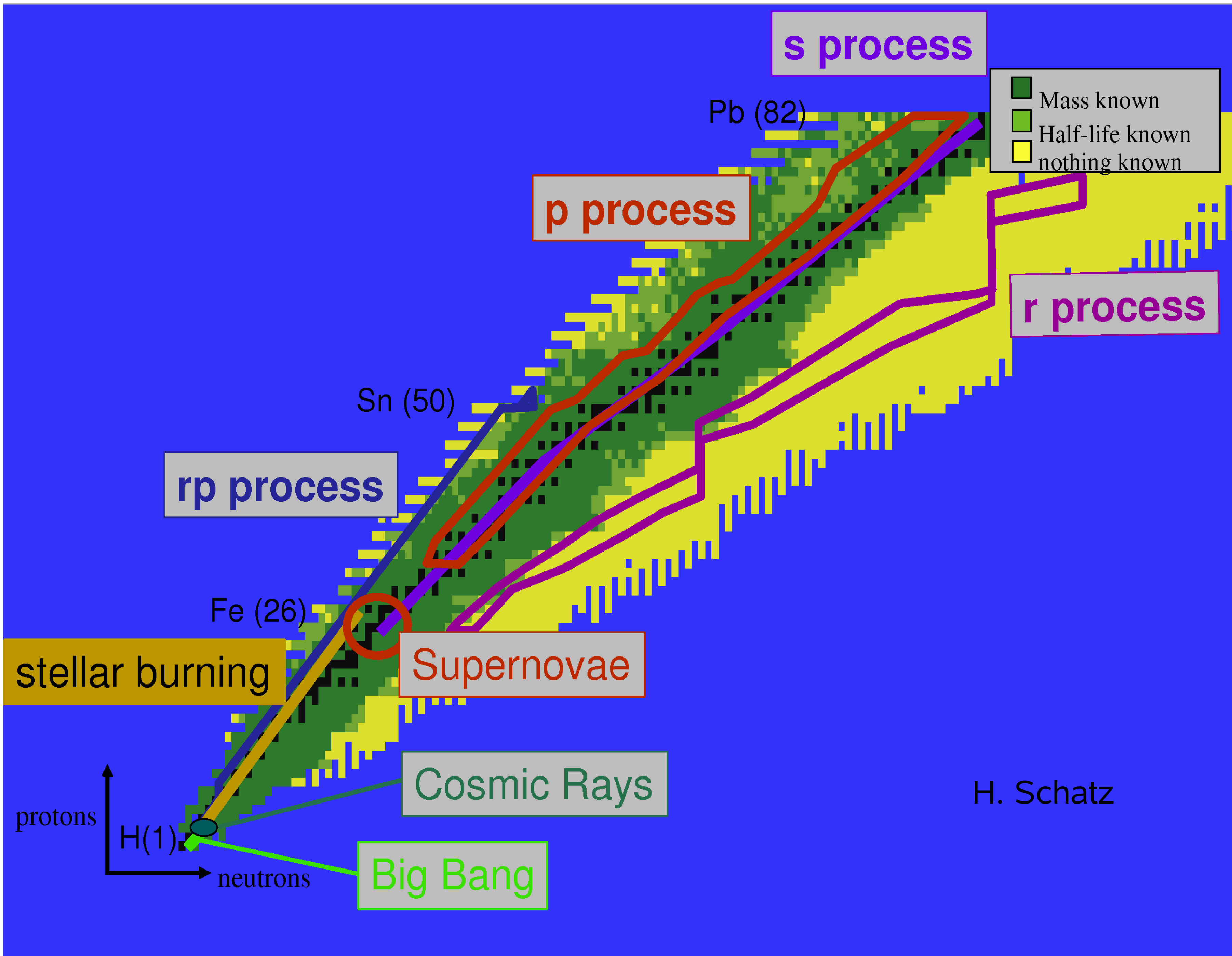


F. Käppeler



P. Möller

All Processes in the Nuclear Chart



Mass predictions (far from stability):

Is there an accuracy limit?

existing approaches:
Finite Range Droplet Model,
Extended Thomas Fermi,
Hartree-Fock Boguliubov

Comparison to NUBASE (2001) // (2003)

FRDM (1992) σ_{rms} = 0.669 // **0.616** [MeV]
ETFSI-Q (1996) σ_{rms} = 0.818 // **0.729** [MeV]

with new deformation shapes/symmetries FRDM expects to improve by about 0.1

HFB-2 (2002) σ_{rms} = 0.674 [MeV]
HFB-3 (2003) σ_{rms} = 0.656 [MeV]
HFB-4 (2003) σ_{rms} = 0.680 [MeV]

HFB-8 (2004) σ_{rms} = 0.635 [MeV]
HFB-9 (2005) σ_{rms} = **0.733** [MeV]

HFB-14 (2007) σ_{rms} = 0.729 [MeV]

Other microscopic approaches

- united energy density functional (UENDEF)
- relativistic mean field

Test with Rare Isotope Beam Facilities

- RIKEN, GSI/FAIR, RIA2?
- and related theory efforts (e.g. ENSAR)

“Historical” Burning Processes (B^2FH)

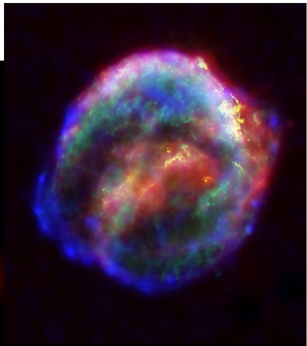
- H-Burning
- He-Burning
- alpha-Process
- e-Process
- s-Process
- r-Process
- p-Process
- x-Process

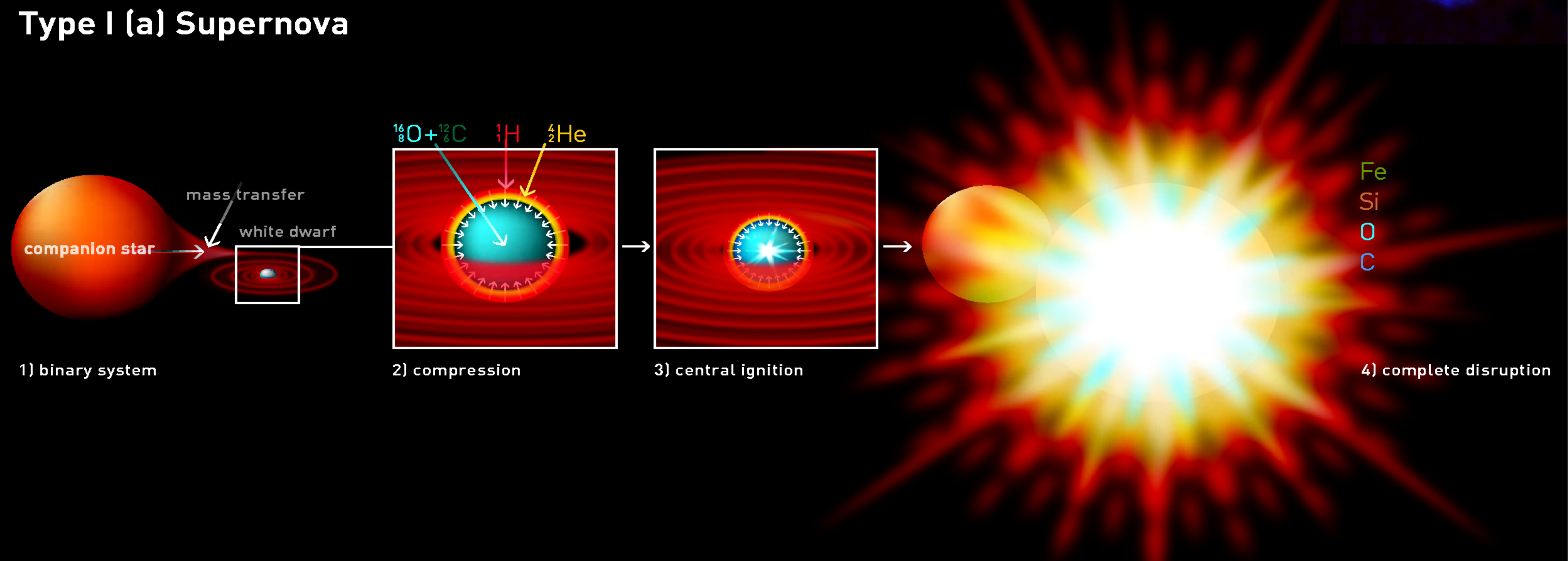
Present Understanding

- H-Burning
- He-Burning
- expl. C, Ne, O-Burning, incomplete Si-Burning
- explosive Si-Burning
- about 70% normal freeze-out, Y_e=0.42-47, about 30% alpha-rich freeze-out, Y_e=0.5
- s-Process (core and shell He-burning, neutrons from alpha-induced reactions on ^{22}Ne and ^{13}C)
- r-Process (see below)
- p-Process (see below)
- x-Process (light elements D, Li, Be, B [big bang, cosmic ray spallation and neutrino nucleosynthesis])

- rp-Process and νp-Process not yet known

Type Ia Supernovae from Accretion in Binary Stellar Systems



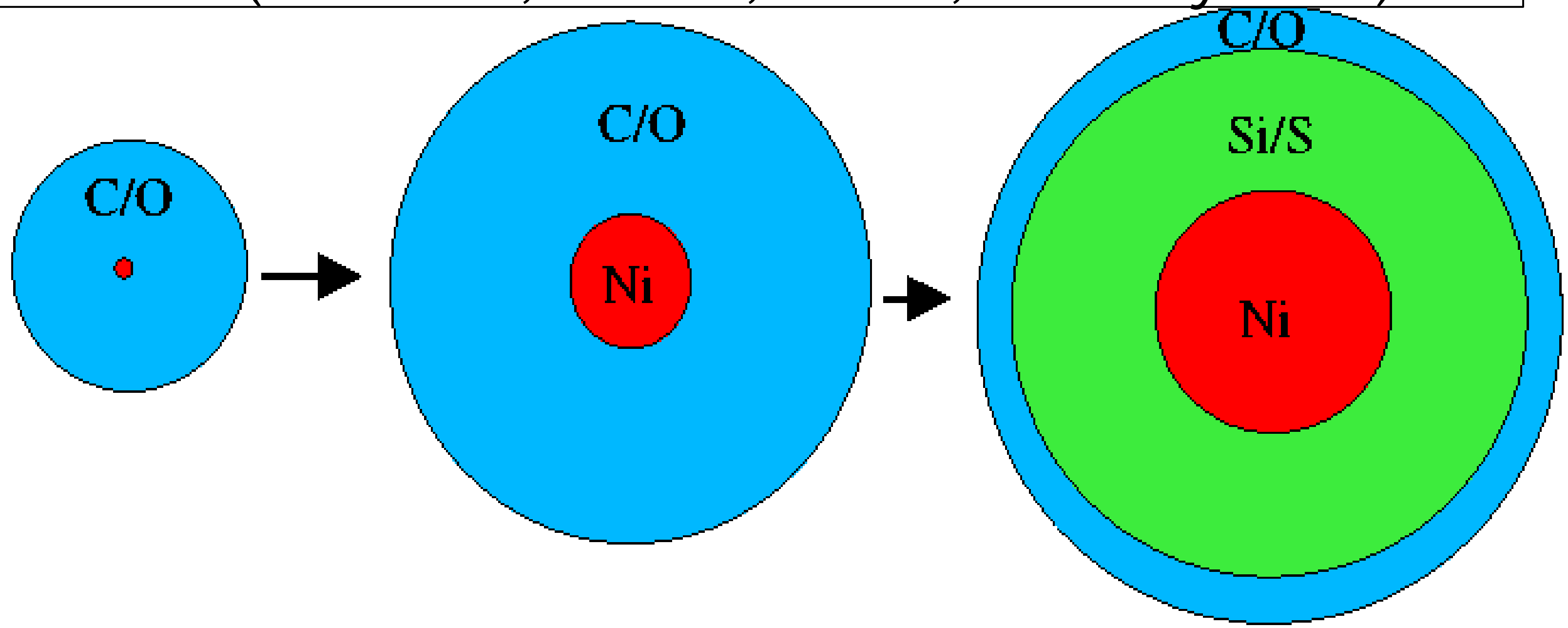


binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- white dwarfs (novae, type Ia supernovae)
- neutron stars (type I X-ray bursts, superbursts?)

Back of the Envelope SN Ia

e.g. W7 (Nomoto, Thielemann, Yokoi 1984); delayed detonations (Khokhlov, Höflich, Müller; Woosley et al.)



$M_{ch} \approx 1.4 M_\odot$ of $^{12}C/^{16}O$=1 WD → 1.398776 $M_\odot$ ^{56}Ni

→ 2.19×10^{51} erg - $E_{grav} \approx (5-6) \times 10^{50}$ erg

reduction due to intermediate elements like Mg, Si, S, Ca

→ 1.3×10^{51} erg

in spherically symmetric models description of the burning front propagation (with hydrodynamic instabilities) determines outcome!

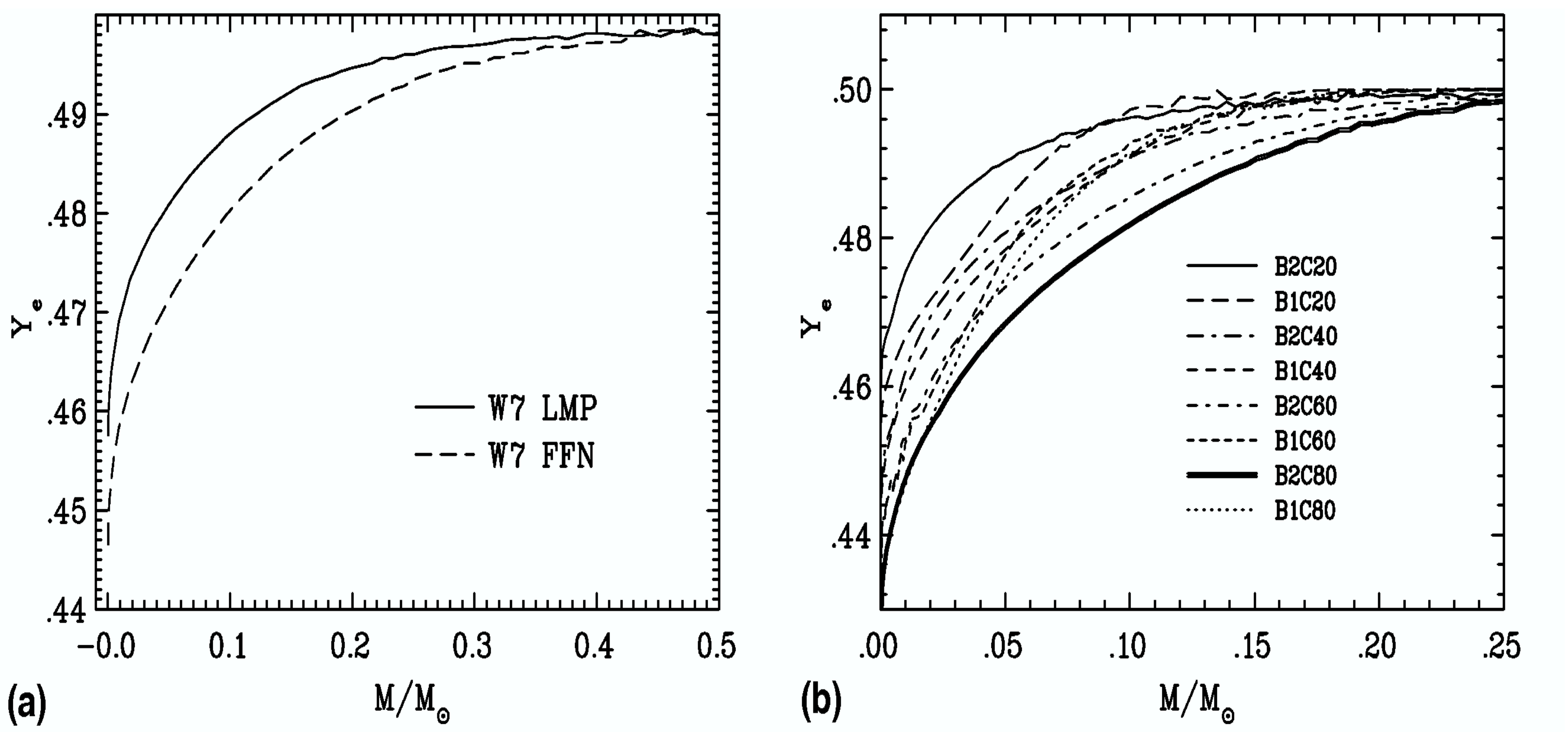
Neutronization via electron capture
(high Fermi energies at central densities)

^{56}Ni

^{54}Fe, ^{58}N

^{56}Fe

^{50}Ti,^{54}Cr



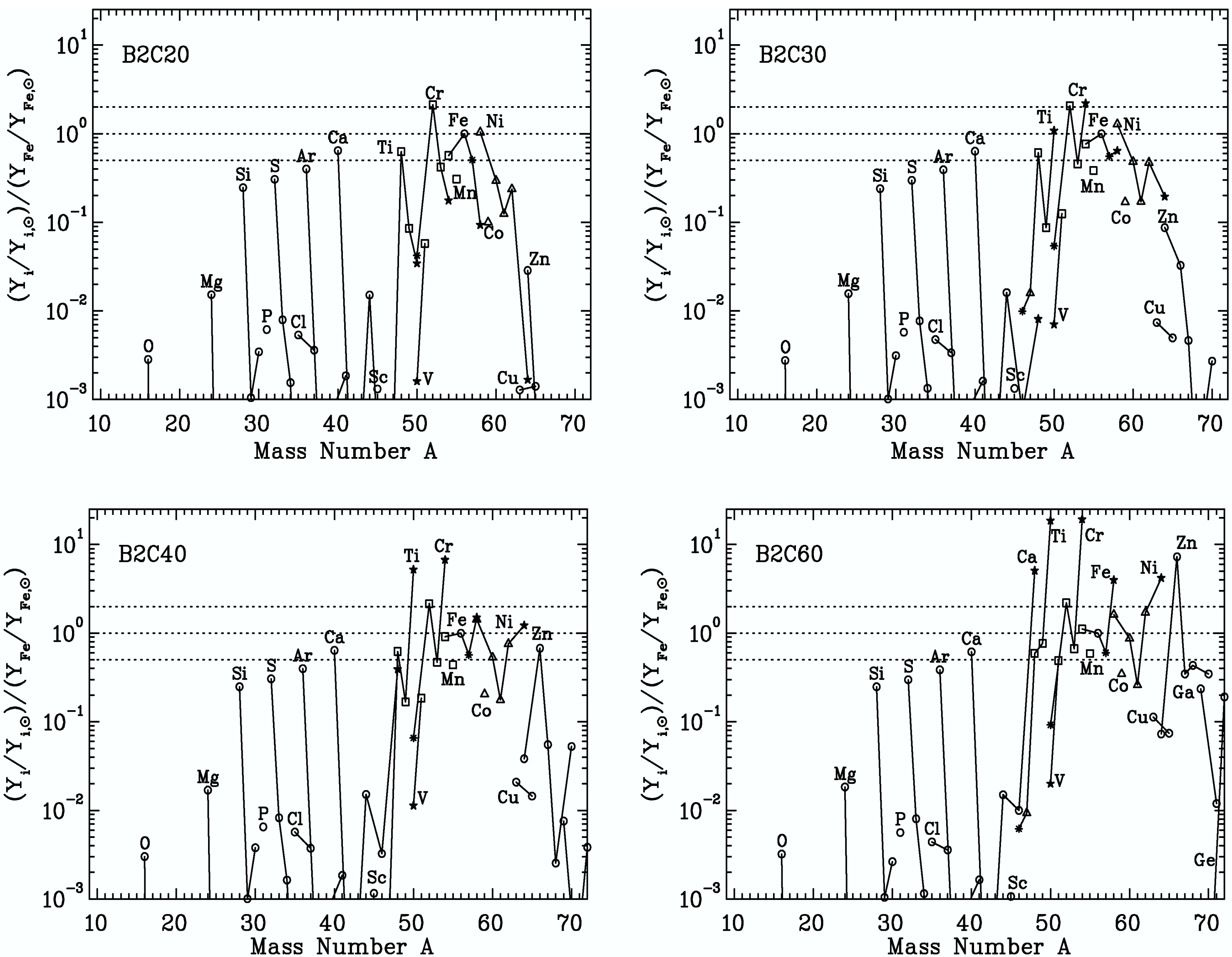
(a) Test for influence of new shell model electron capture rates
(including pf- shell Langanke, Martinez-Pinedo 2003)

(b) Test for burning front propagation speed (Brachwitz et al. 2001)

direct influence on dominant Fe-group composition resulting from SNe Ia

Ignition density determines Ye and neutron-richness of (60-70% of) Fe-group

FKT et al. (2004)



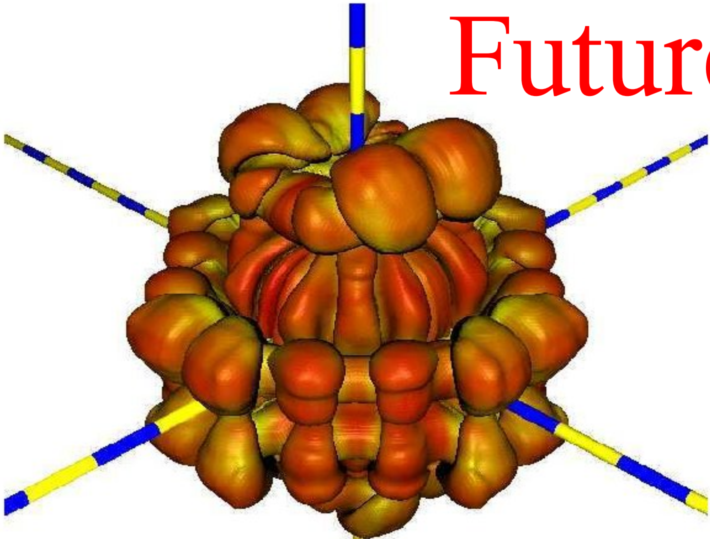
results of explosive C, Ne, O and Si-burning:
Fe-group to alpha-elements 2/1-3/1

SNe Ia dominate Fe-group, over-abundances by more than factor 2 not permitted

→

maximum central density 3 10^9 gcm^{-3}

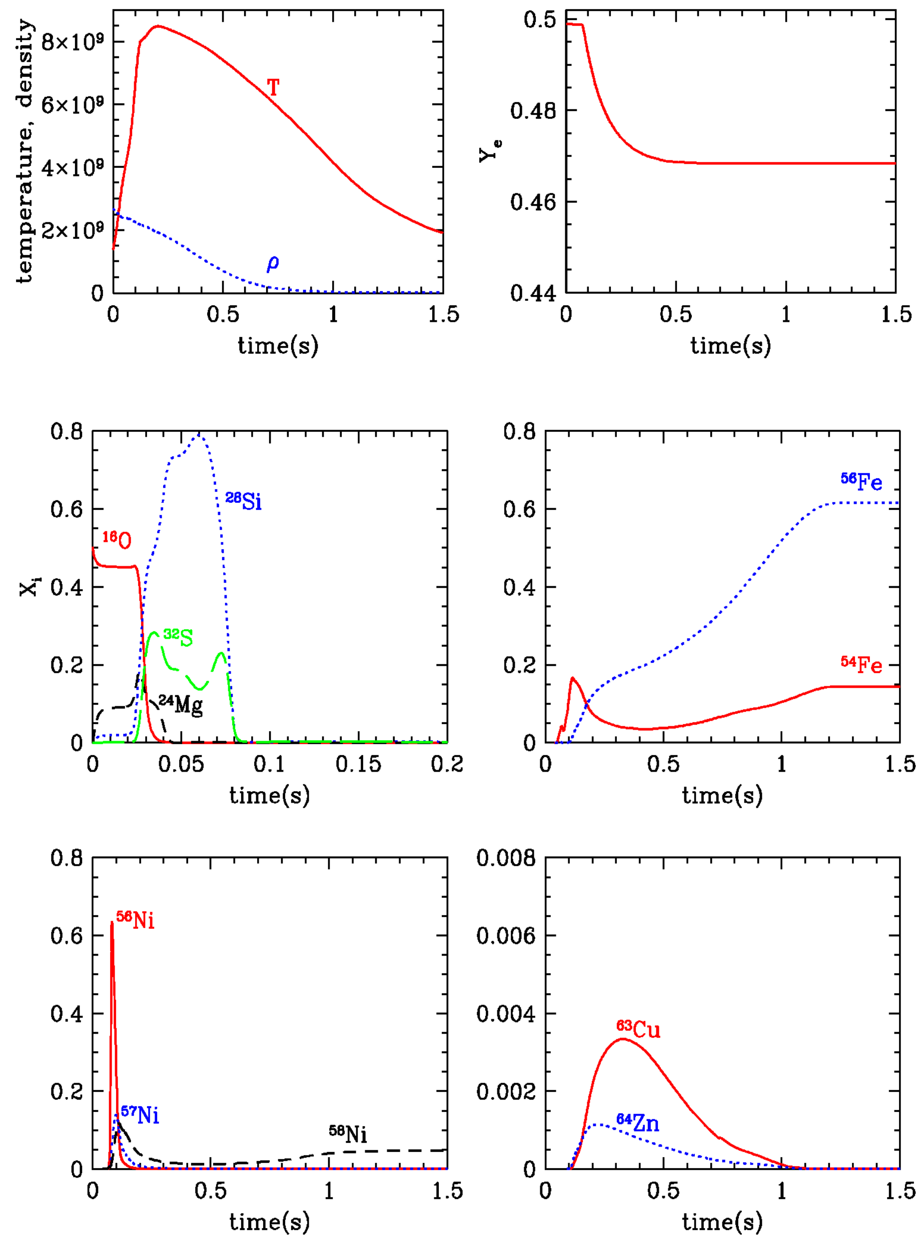
Future 3D Models



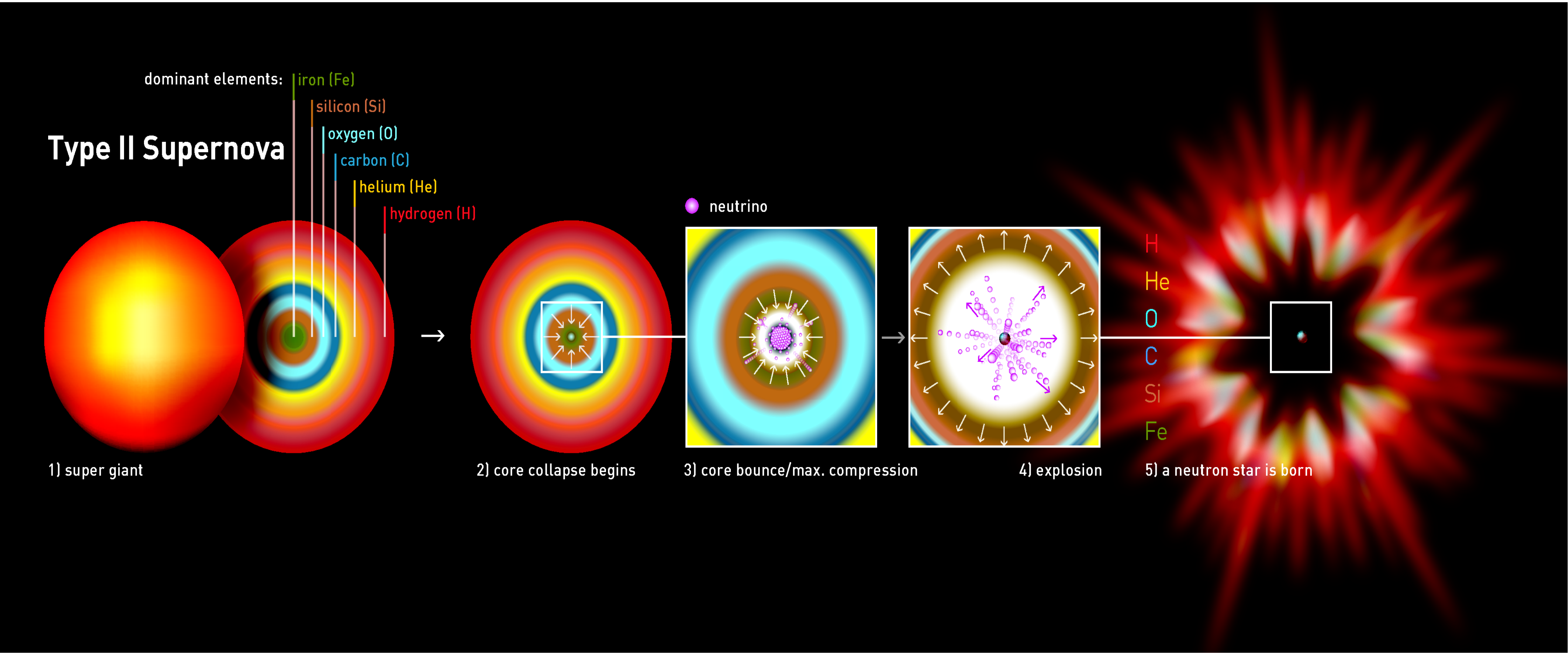
Travaglio, Reinecke, Hillebrandt, FKT (2004, 3D nucleosynthesis with tracer particles)

consistent treatment needed instead of parametrized spherical propagation, MPA Garching (Röpke et al. 2007), U. Chicago/SUNY Stony Brook (Calder et al. 2007)

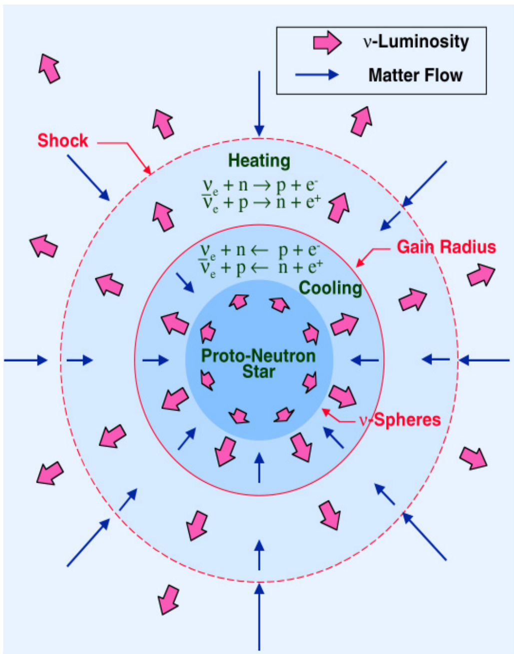
- *distribution of ignition points uncertain*
- *hydrodynamic instabilities determine propagation of burning*
- *deflagration/detonation transition*



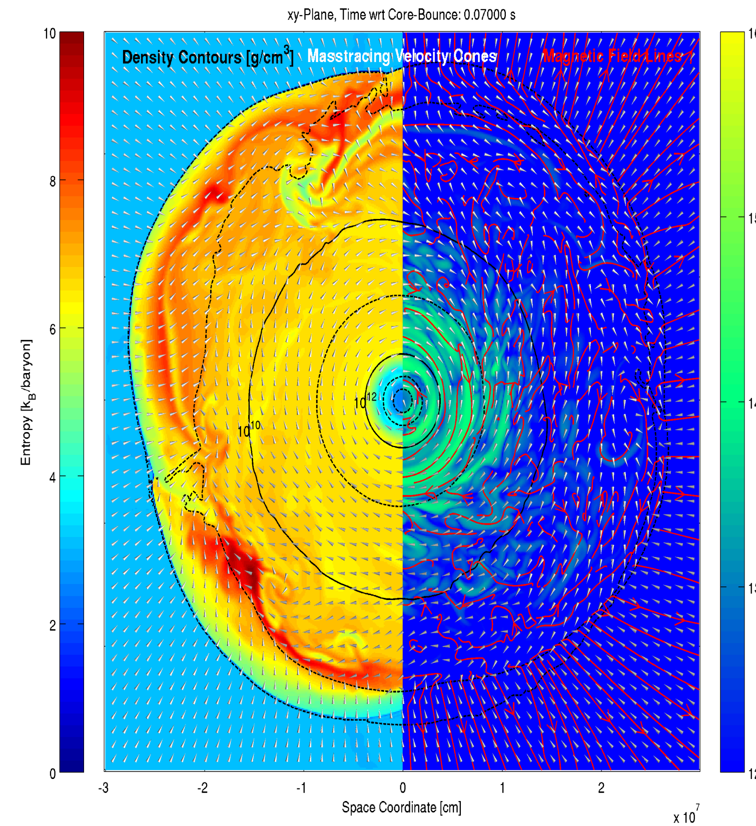
Core Collapse Supernovae from Massive Stars



Neutrino-driven Core Collapse Supernovae



Simulations with Rotation and Magnetic Fields



entropy and magnetic field strength 0.07s after bounce

grav. wave signal should be seen with LIGO at 10kpc

$\nu_e + n \leftrightarrow p + e^-$ heating

$\bar{\nu}_e + p \leftrightarrow n + e^+$

$\nu_e + A' \leftrightarrow A + e^-$ opacity

$\nu + N \leftrightarrow \nu + N$

$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ thermalization

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\nu = \nu_e, \nu_\mu, \nu_\tau$ source terms

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

also

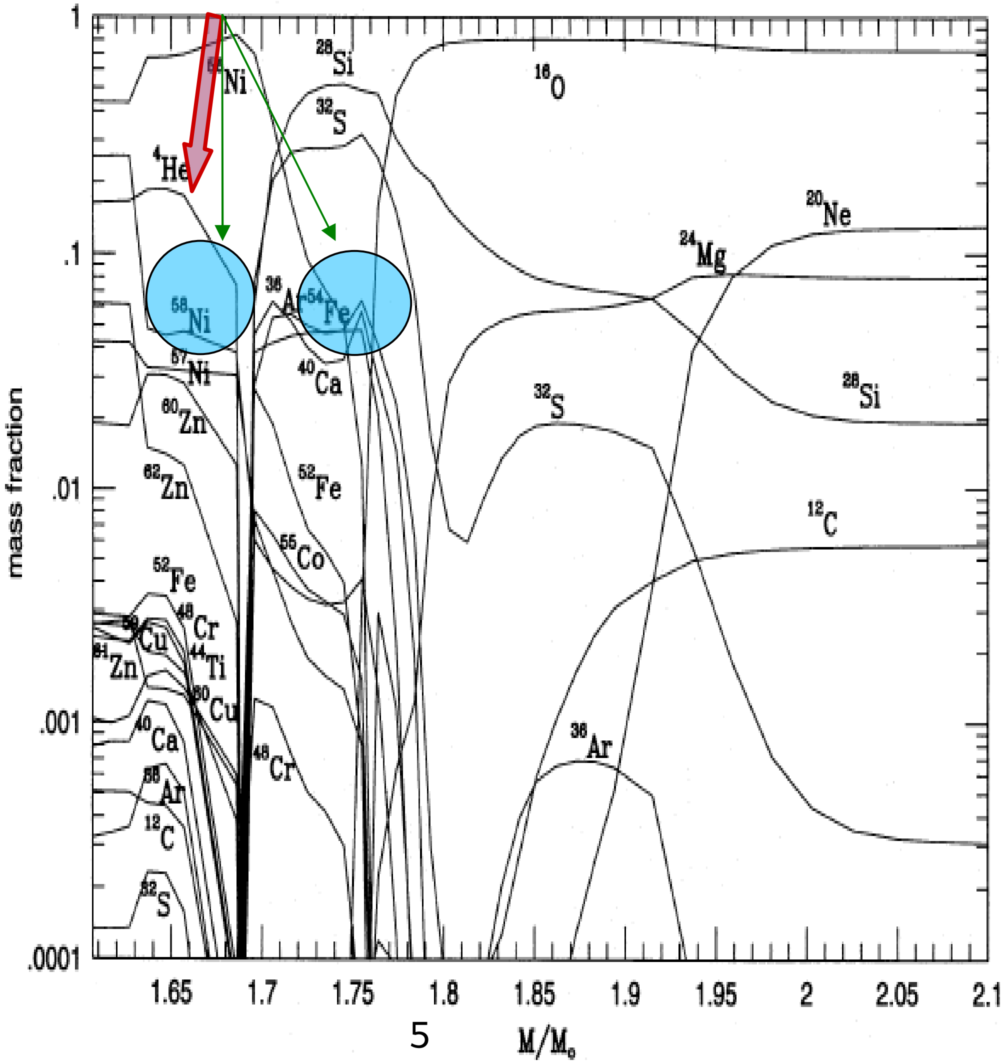
$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

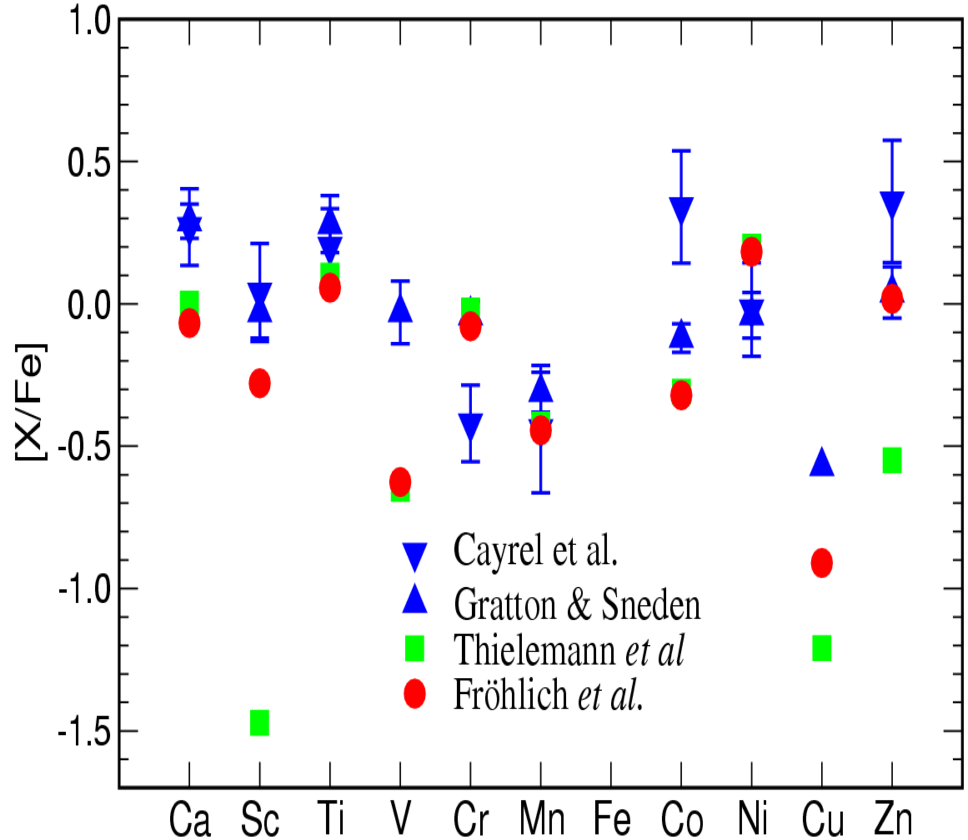
and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Nucleosynthesis problems in “induced” piston or thermal bomb models

utilized up to present to obtain explosive nucleosynthesis yields with induced explosion energies of 10^{51} erg

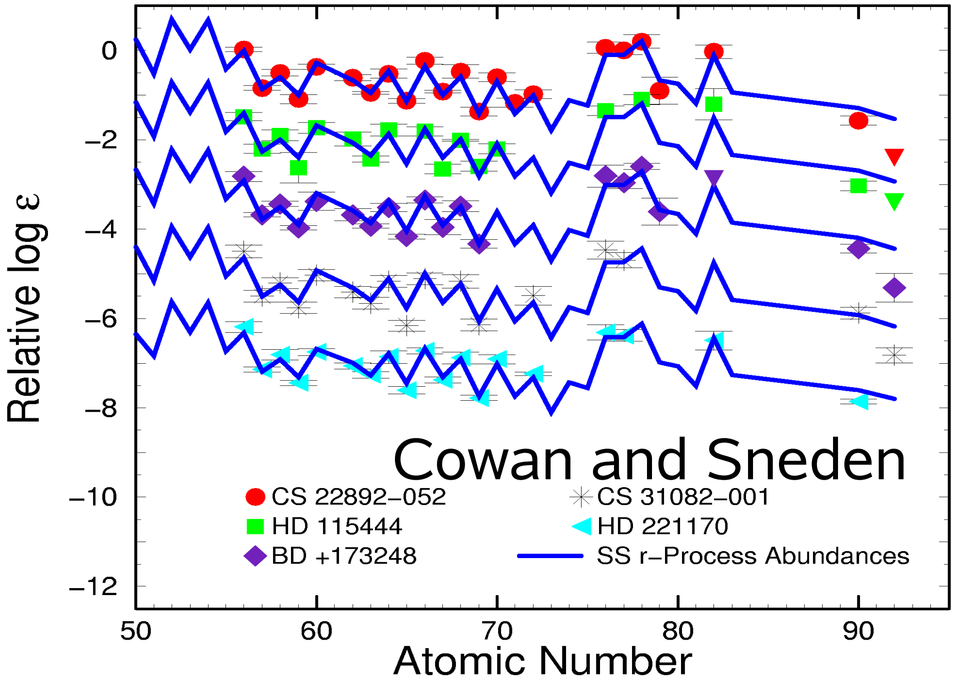




Fröhlich et al. (2004, 2006a), see also Pruet et al. (2005), improved Fe-group composition

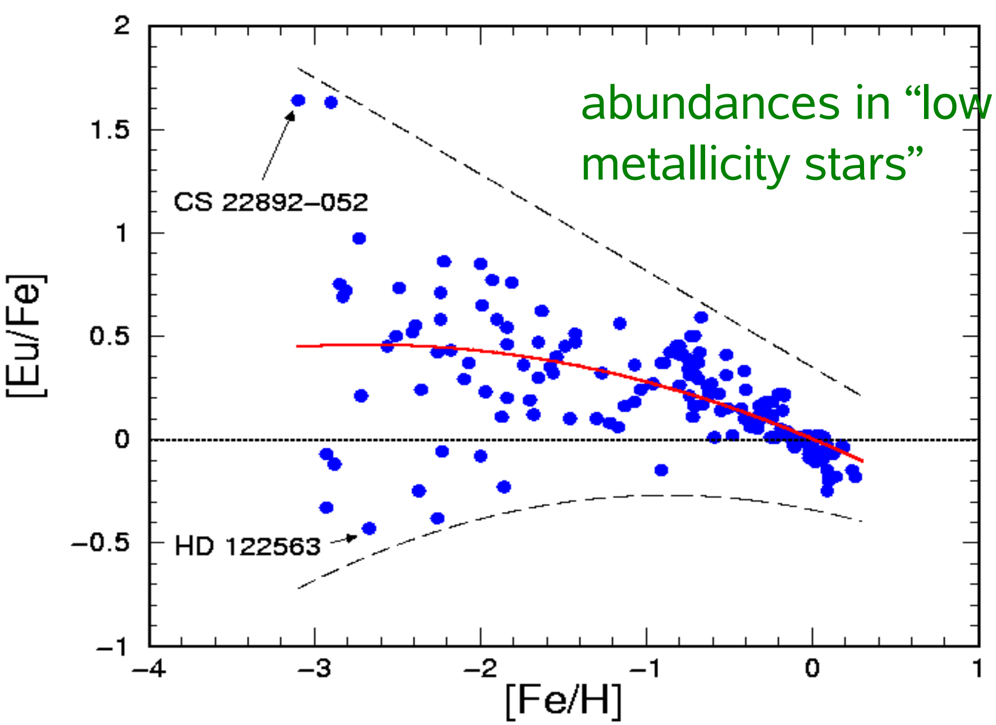
prior results of Thielemann, Nomoto, Woosley, Chieffi .. made use of initial stellar structure (and Y_e!) when inducing artificial explosion. This neglects the effect of the explosion mechanism on the innermost zones, causes strange overproductions of Ni isotopes and does not go much beyond Ni!

Observational Constraints on r-Process Sites

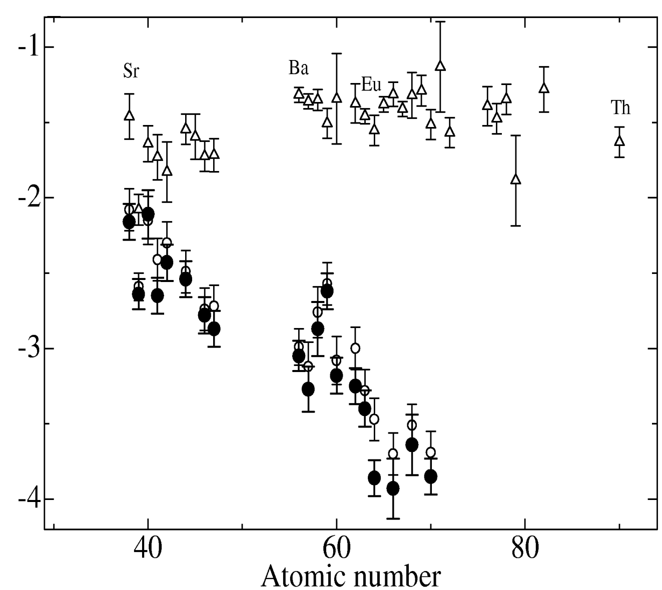


apparently uniform abundances above Z=56 (and up to Z=82?) -> "unique" astrophysical event which nevertheless consists of a superposition of ejected mass zones

"rare" event, which must be related to massive stars due to "early" appearance at low metallicities(behaves similar to SN II products like O, but with much larger scatter)



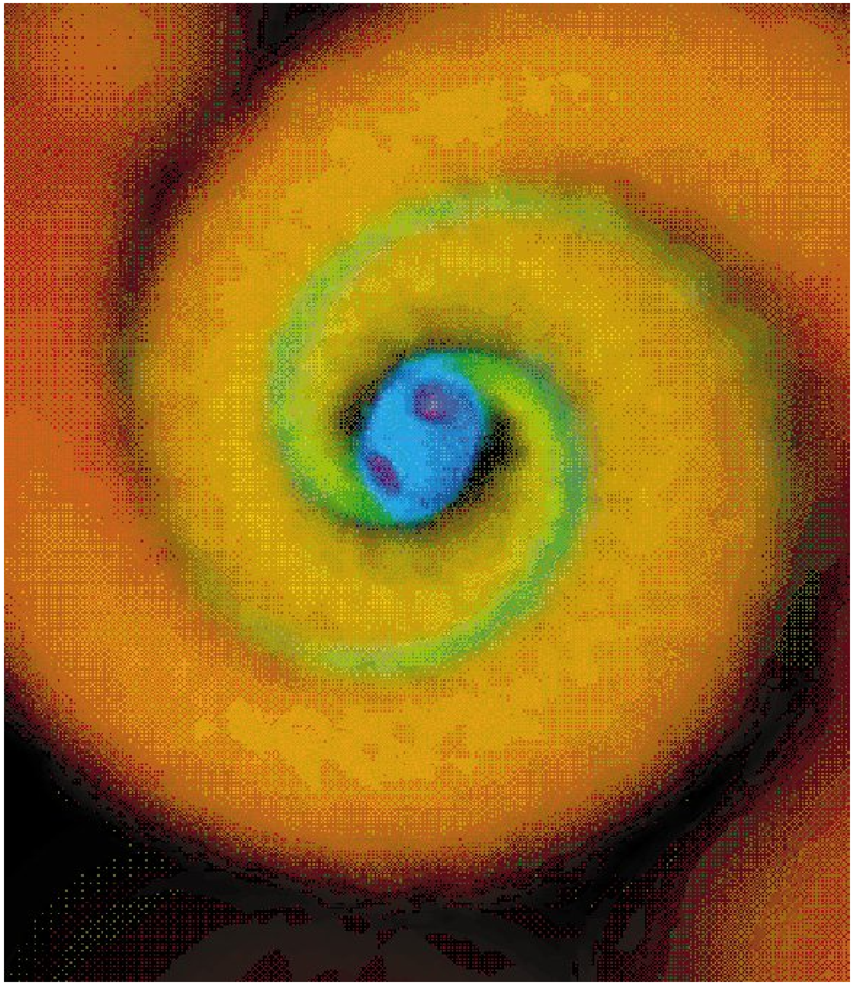
Observations of the weak r-process?



Honda et al. (2007)

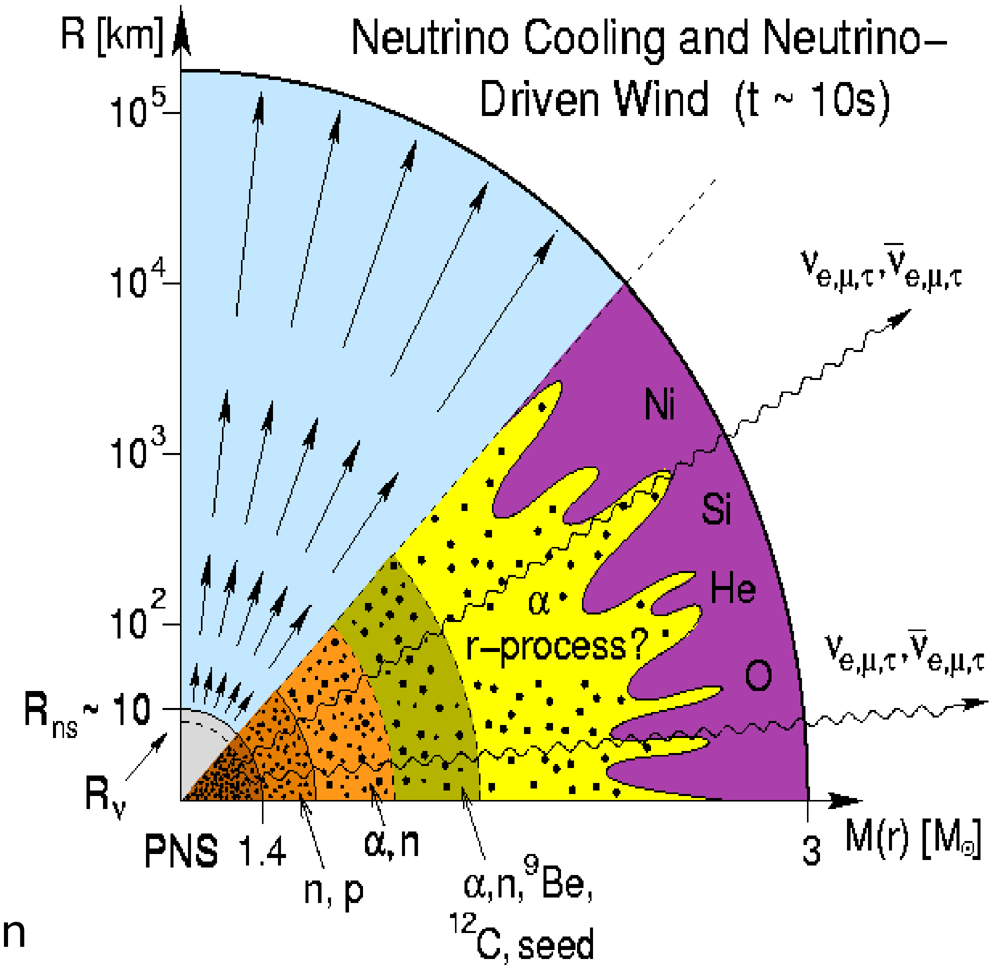
What is the site of the r-process?

from S. Rosswog



NS mergers, BH-NS mergers, problems: ejection too late in galactic evolution
(or alternatively polar jets from supernovae, Cameron 2003)

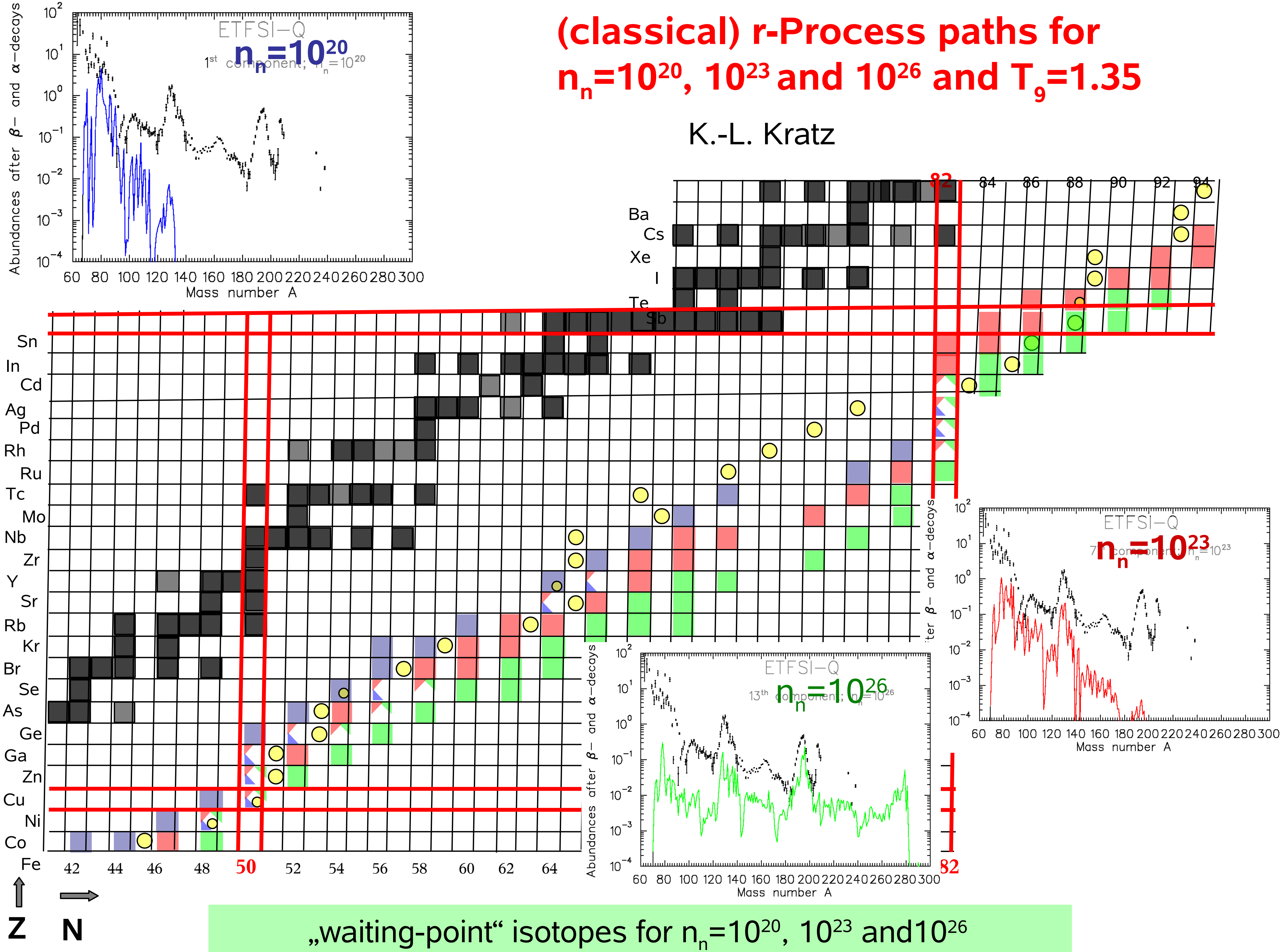
from H.-T. Janka



SN neutrino wind, problems: high enough entropies attained?
neutrino properties???

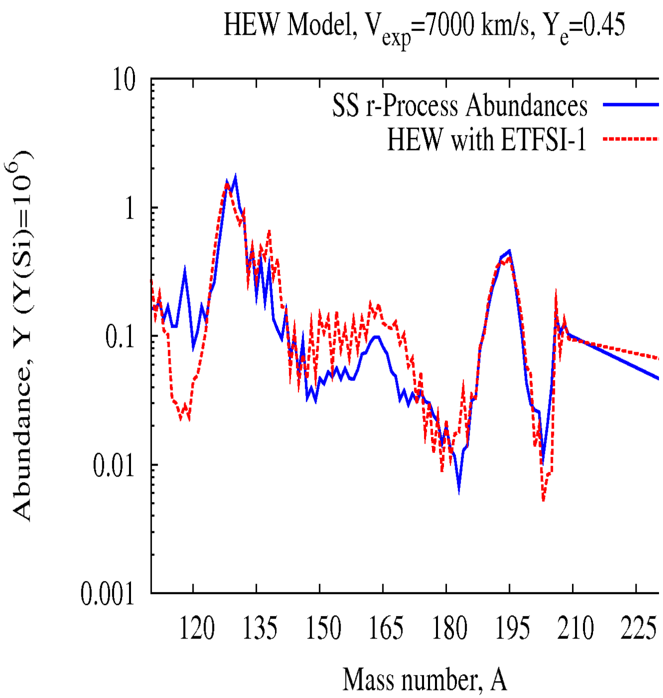
(classical) r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26} and $T_9=1.35$

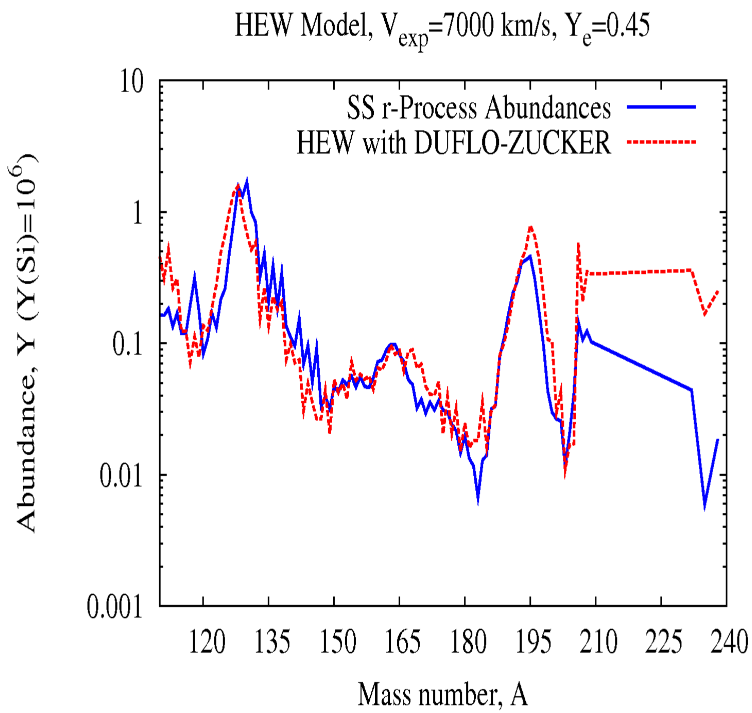
K.-L. Kratz

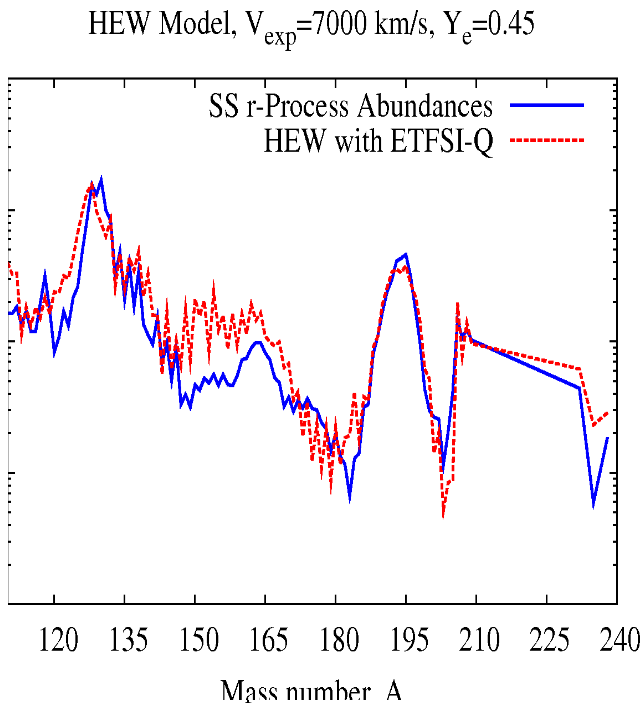


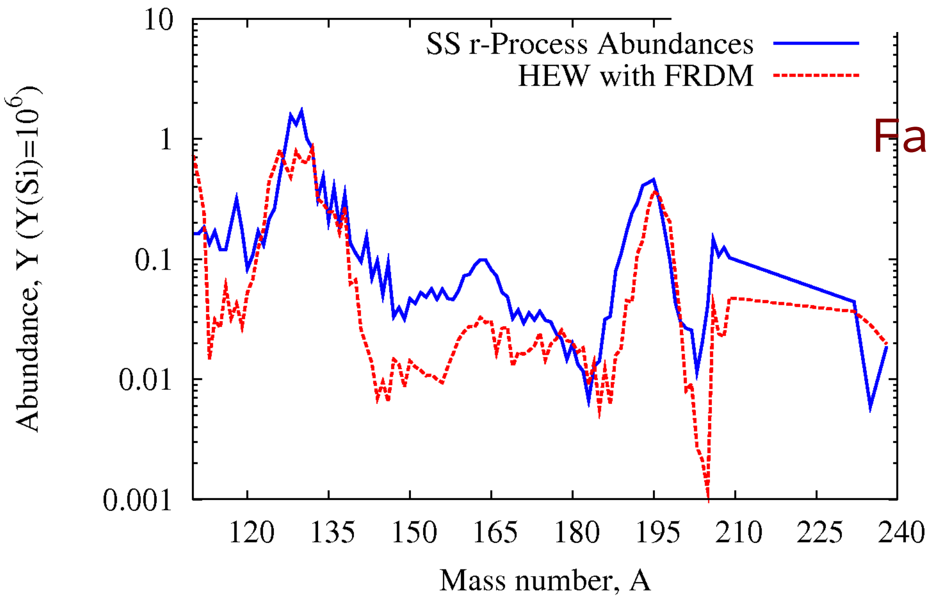
„waiting-point" isotopes for $n_n=10^{20}$, 10^{23} and 10^{26}

Superposition of entropies for different mass models

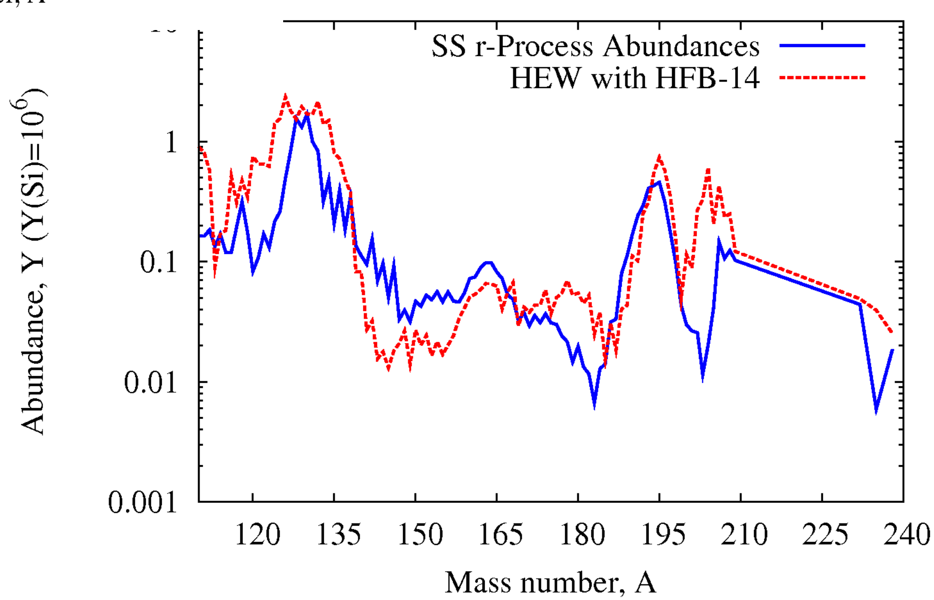








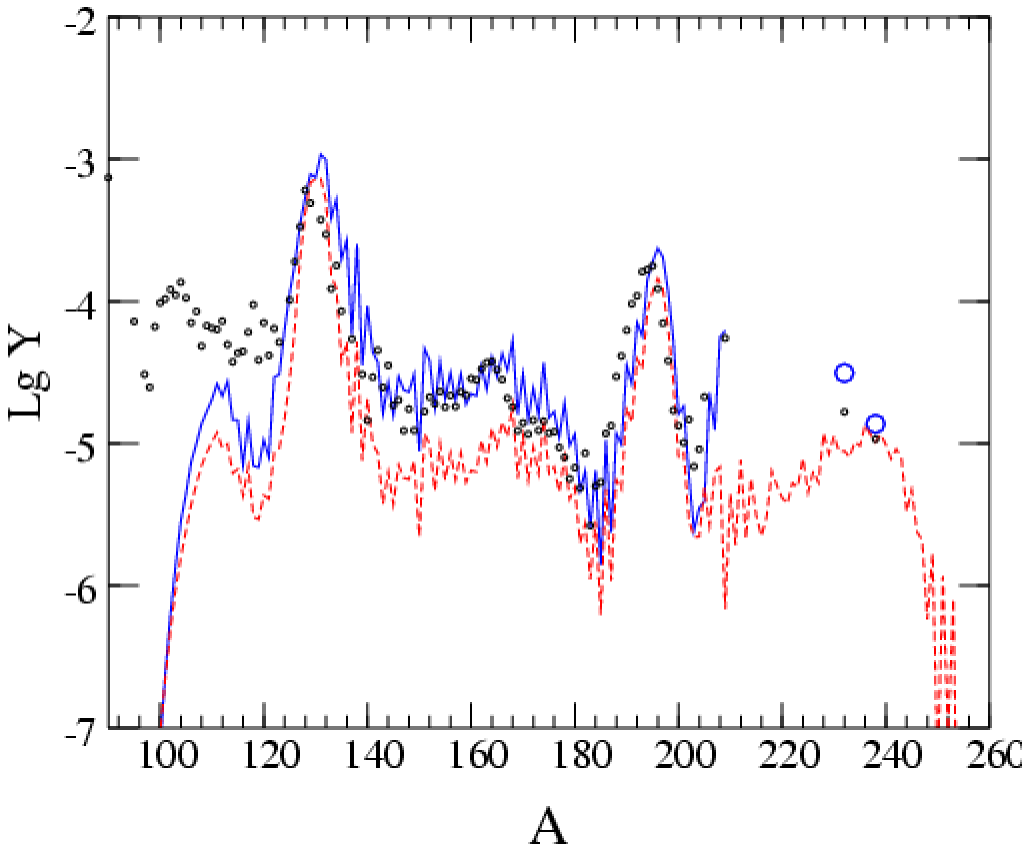
Farouqi et al. (2008)



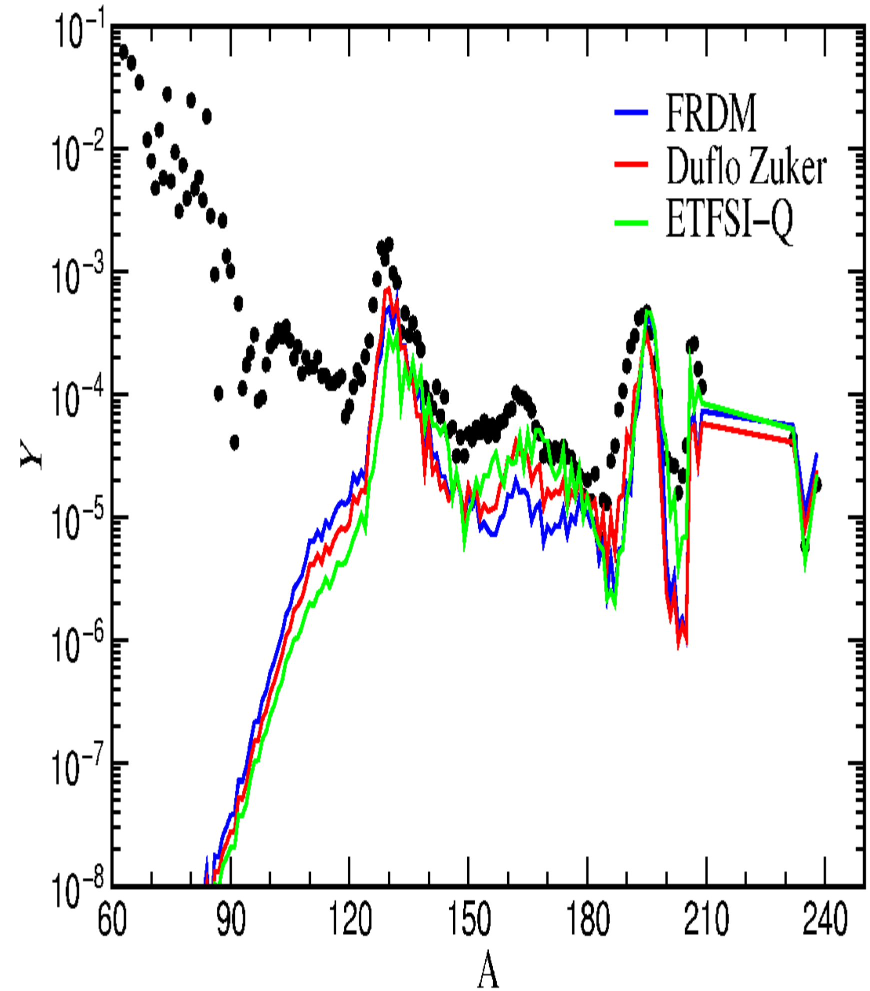
we can test nuclear models with assumed conditions from stellar explosions, but the site is still open

Fission Cycling in Neutron Star Mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999 ($Y_e = 0.1, n/Seed = 238$).



Panov and FKT (2007) with parametrized fission yield contribution



Martinez-Pinedo et al. (2007)

in principle contradicted from gal. evol. calc., but similar conditions in SN polar jets? (Cameron 2003)